

Development of Methodology for Determining Risk
Assessment When Sludge is Applied to Land

Cornell Univ.
Ithaca, NY

Prepared for

Health Effects Research Lab.
Cincinnati, OH

Aug 81



BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

P881-240012

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

EPA-600/1-81-058
August 1981

DEVELOPMENT OF METHODOLOGY FOR DETERMINING RISK ASSESSMENT
WHEN SLUDGE IS APPLIED TO LAND

by

Peter R. Jutro
Anil Nerode
Cornell University
Ithaca, New York 14853

9 1/8"

Grant No. R805781

Project Officers

Norman E. Kowal
Epidemiology Division
Health Effects Research Laboratory
Cincinnati, Ohio 45268

G. Kenneth Dotson
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

HEALTH EFFECTS RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

EPA-287 (Cin.)
(4-76)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO. PB81 240012
4. TITLE AND SUBTITLE Development of Methodology for Determining Risk Assessment when Sludge is Applied to Land		5. REPORT DATE
7. AUTHOR(S) Peter R. Jutro and Anil Nerode		6. PERFORMING ORGANIZATION CODE
9. PERFORMING ORGANIZATION NAME AND ADDRESS Cornell University Ithaca, New York 14853		8. PERFORMING ORGANIZATION REPORT NO.
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Health Effects Research Laboratory 26 W. St. Clair St. Cincinnati, Ohio 45268		10. PROGRAM ELEMENT NO. CAYB1B
		11. CONTRACT/GRANT NO. R805781
		13. TYPE OF REPORT AND PERIOD COVERED Final, 5/15/78 - 10/15/80
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		
16. ABSTRACT This project explored the feasibility of developing a risk assessment methodology that could be applied to sludge management decision making. It examined cadmium, since this substance is one of the best studied and most extensively reported contaminants. The methodology developed allows determination of the proportion of the population experiencing given levels of exposure to a toxic substance under specified management strategies. In addition, it provides for the evaluation of the damage caused by such exposure. When both the dosage-response analysis and the exposure population analysis are joined, the distribution of population into levels of response can be established. Each requires separate categories of data. The first is the result of controlled experiments and carefully designed epidemiological statistical studies. The second consists of ongoing data bases on a national scale, including both measurements of background levels of the toxic substance and data on the actual levels at the various stages of the disposal and dispersal procedures. This report establishes that these data bases are required. The problems associated with both categories of data are considered and discussed.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT Release to Public		19. SECURITY CLASS (This Report) Unclassified
		20. SECURITY CLASS (This page) Unclassified
		21. NO. OF PAGES
		22. PRICE

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

DISCLAIMER

This report has been reviewed by the Health Effects Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

ii

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay among its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Health Effects Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report describes an attempt to determine the feasibility of developing a risk assessment methodology that could be applied to wastewater sludge decision making. Cadmium is used as an example of the application of the methodology since it is one of the best studied pollutants.

James B. Lucas
Acting Director
Health Effects Research Laboratory

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

iii

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

PREFACE

The objective of this study was to evaluate the applicability of utilizing risk assessment methodology to assist in the determination of sludge management decisions.

The identification and prevention of "unreasonable" risks to public health and safety from environmental pollution has, in recent years, become a central objective of federal legislation and regulation. Few federal laws provide guidance regarding the definition of crucial terms such as "risk," "unreasonable risk" or "risk assessment". Perhaps the closest approach to a definition is found in the Federal Insecticide, Fungicide, and Rodenticide Act, which states that, for pesticides,

"The term 'unreasonable adverse effects on the environment' means any unreasonable risk to man or the environment, taking into account the economic, social, and environmental costs and benefits..."(1)

It is clear that this definition ultimately begs the question of what actually makes a risk "unreasonable". Further understanding of the legislative perception of risk assessment may be gleaned from a discussion of unreasonable risk in the House Report accompanying the Toxic Substances Control Act:

"In general, a determination that a risk associated with a chemical substance or mixture is unreasonable involves balancing the probability that harm will occur and the magnitude and severity of that harm against the effect of proposed regulatory action on the availability to society of the benefits of the substance or mixture."(2)

Such an analysis leads one to think of risk assessment as a process that includes both an inquiry into the probability and severity of expected harm and a balancing of the costs and benefits of preventive regulation.

BEGIN
LAST LINE
OF TEXT

3/8"

iv

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Our research supports the notion that there are two components involved in such an analysis, and concedes that under certain circumstances they may even be related in a fairly straightforward way, since the more probable or serious the harm, the greater the benefits of regulation are likely to be. Nevertheless, these are two very different analytical problems, and we have chosen to confine this analysis to that of scientifically and probabilistically evaluable data that can generate an idea of the nature and magnitude of risk. Not examined are the societal decisions that are then made on the basis of this and other information, which represent the degree of safety which society finds requisite.

In the past, we have observed the results of the seductive temptation to generate and to assign maximum allowable concentration values for each of the various components of sewage sludge that were perceived to be potentially hazardous to some element of the population. Management decisions were then made on the basis of whether any particular option would or would not cause the maximum allowable concentration to be exceeded.

We find this implied ease of enforcement to be illusory. There can be no sharp division between safe and unsafe that is appropriate for all contexts. Moreover, our perceptions of such distinctions are by necessity clouded by the uncertainties of limited knowledge and perceptual bias. We have found it to be more appropriate to assess management decisions on the basis of measures of probability, i.e., the probability that certain untoward effects will follow specific management decisions. This document reports a method for undertaking such a procedure.

This project was proposed in the fall of 1977 and was begun in mid-1978. A draft final report was provided to the Agency in the spring of 1980. Comments upon and suggestions for revision of the report were provided by the Agency in the summer of 1980. We believe we have responded to all reviewers' comments and have incorporated suggested changes into the report. In addition, however, we have taken advantage of

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

the opportunity to make certain substantial changes in the exposition that reflect continuing research undertaken by the investigators following the end of the grant period. Our reference materials, therefore, extend through early 1980, whereas the analytical methodology represents research undertaken through the end of 1980.

6-1/2"

9 1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

vi

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

ABSTRACT

This project attempted to determine the feasibility of developing a risk assessment methodology that could be applied to sludge management decision making. It examines one important substance, cadmium. Since cadmium is one the of the best studied and most extensively reported contaminants, it provides a best-case vehicle for establishing the feasibility of the method.

The methodology developed can allow determination of what proportion of the population experiences given levels of exposure to a toxic substance under specified management strategies. Supposing such empirical determination to have been completed, it provides for the evaluation of the damage caused by such exposure. It is only when both the dose-response analysis and exposure population analysis are joined that the distribution of population into levels of response can be established. Each requires separate categories of data. The first category is the result of controlled experiments and carefully designed epidemiological statistical studies. The second category consists of ongoing data bases on a national scale, including both measurements of background levels of the toxic substance and data on the actual levels at the various stages of the disposal and dispersal procedures. In the report, it is established that these data bases are required. The problems associated with both categories of data are considered and discussed.

To determine feasibility of risk assessment, the study began an exploratory analysis of modeling, data bases and transfer characteristics needed for an actual risk assessment. Since systematic risk evaluation as a subject is in its infancy, many potentially necessary data bases do not currently exist, and those that do exist often are not adequate to describe

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

the transfer features required. Existing data bases were reanalysed on a single systematic basis in a form which was suitable for undertaking the exercise. This study used non-parametric, robust and resistant statistics for determining empirical distributions characterizing the desired transfer characteristics.

On the basis of the study, it appears feasible to use risk assessment for decision making on toxic substance disposal. Macroscopic models often give valuable information because they summarize information which, when massed properly, is intelligible and stable, but where the actual phenomena involved are governed locally by unknown exact equations or chance phenomena. This report concludes that much of the required data is being gathered currently, but in an inefficient fashion not appropriate for risk assessment. It will be necessary to formulate appropriate data gathering and record keeping protocols. It anticipates that this will take place as regulators and industry realize that the only way to defend the prudence of their decisions in a rigorous way is through such risk analysis using the best current data and techniques.

This report was submitted in fulfillment of Grant No. R 805781 by Cornell University under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from May 15, 1978 to October 15, 1980, and work was completed December 15, 1980.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

CONTENTS

	<u>Page</u>
Foreword	iii
Preface	iv
Abstract	vii
Figures	x
Tables	xii
Acknowledgements	xiii
1) Introduction	1
2) Conclusions	13
3) Recommendations	15
4) Methods: The Application of Distribution Models to Risk Assessment in Sludge Management	18
5) Sources of Sewage Sludge; Their Role in Environmental Loading of Cadmium	49
6) Application Rates as Determinants of Soil Concentration.....	68
7) Uptake in Plants in Response to Soil Cadmium Levels	80
8) Animal Response to Crops Grown on Sludged Plots	102
9) Exploratory Association of Air Cadmium Level with Mortality Attributed to Three Categorical Factors	105
References	121
Bibliography	123

BEGIN
LAST LINE
OF TEXT

3/8"

ix

PAGE NUMBER

EPA 267 (Ch. 1)
(4-76)

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

FIGURES

<u>Number</u>	<u>Page</u>
1. Preliminary schematic outline of risk assessment system.....	5
2. Idealized subsystems in the pattern of entry, movement, and consequences of a toxic substance in the environment.....	19
3. Health effects of sludge disposal alternatives.....	20
4. Points for control in sludge management.....	21
5. Methods of control in sludge management.....	22
6. Agents for exercise of control in sludge management.....	23
7. Health effects from land application of sludge.....	24
8. Stage I.....	26
9. Stage II.....	30
10. Stage III.....	32
11. Stage IV.....	33
12. Stage V.....	35
13. Stage VI.....	37
14. Stage VII.....	39
15. Stage VIII.....	41
16. Stage IX.....	43
17. Stage X.....	45
18. Stage XI.....	46
19. Stage XII.....	48
20. Yearly summaries of biweekly sampling at six plants.....	53
21. Distribution of sludge output by cadmium concentration (excluding thirteen largest cities and Boston).....	61
22. Percent distribution of sludge by cadmium concentration for four large cities.....	64
23. Percent distribution of sludge by cadmium concentration for some large cities.....	65
24. Cadmium concentrations in the 0-15 CM stratum by cumulative applied cadmium.....	74
25. Soil cadmium concentrations, 0-15 CM depth, by cumulative applied cadmium, North Series.....	76
26. Soil cadmium concentrations, 0-15 CM depth, by cumulative applied cadmium, South Series.....	77
27. Soil cadmium concentrations, by cumulative applied cadmium, untransformed scales.....	79
28. Uptake in leaf for three crops, by soil cadmium levels.....	83
29. Uptake in grain for three crops, by soil cadmium levels.....	85
30. Soybean leaf levels by soil levels, split by salt application rates.....	88
31. Leaf cadmium levels by soil cadmium concentrations.....	90
32. Grain cadmium concentrations by soil concentrations.....	92

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

FIGURES (continued)

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Page

33. Corn grain cadmium by soil cadmium.....	94
34. Leaf and grain levels by soil level.....	96
35. Leaf levels by soil cadmium.....	98
36. Grain levels by soil cadmium.....	99
37. Summary plot: HYPERT-median air cadmium by mortality ratio.	109
38. Summary plot: HYP-median air cadmium by mortality ratio....	110
39. Summary plot: NEPH-median air cadmium by mortality ratio...	111
40. Mortality ratio of HYPERT, by EPA summary air levels of cadmium.....	114
41. Mortality ratio for NEPH, by EPA summary air levels of cadmium.....	115
42. Mortality ratio for HYP, by EPA summary air levels of cadmium.....	116

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

xi

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

TABLES

<u>Number</u>	<u>Page</u>
1. Six Sewage Treatment Plants Sludge Cadmium Concentrations.....	55
2. Secular Characteristics for Six Treatment Plants Sampled at Approximately Two Week Intervals	57
3. Scaled Secular Characteristics Over Two Week Intervals	58
4. Joint Distribution of Treatment Plants by Sludge Protection and Cadmium Level	62
5. Main Effects: Cadmium PPM in Soil	72

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

xii

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

ACKNOWLEDGEMENTS

Professor Raymond Loehr, of Cornell University, was originally a co-principal investigator. Since relinquishing that role, he has remained consistently valuable as a critic, reviewer, and source of new information and insight.

Professor Paul Brandford, of Cornell, originally a co-investigator, contributed extensively to early stages of the research.

The statistical computations were carried out by Dr. Philip Lavori, Dr. Sally Sievers and Pierre Sprey. We express our particular gratitude to these five individuals.

Professor Daniel Goodman of Scripps Institution of Oceanography undertook the design of a preliminary Ecological compartment model. Preliminary analysis of air and water data was undertaken by Reuben Snipper and Chris Hermann. These two endeavors are discussed at the end of the the Introduction.

Several researchers throughout the country graciously made their data available to us. They are cited in the report and references, and we wish to thank them for their cooperation.

Norman Kowal, Donald Ehreth, Thomas Gleason and Kenneth Dotson of the U.S. Environmental Protection Agency provided technical comments which were exceedingly helpful in revising the report.

Professor Richard Dick of Cornell, collaborated with us in the joint sponsorship of a workshop on Risk Analysis and Process Integration in

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Management of Municipal Sludges held at Cornell in May, 1979. We wish to thank him, and the participants in that workshop as well.

Dr. Sheila Jasanoff undertook research on the legal status of risk assessment. Her work made it easier for us to design a model that might allow our work to meet contemporary regulatory needs.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA:
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

xiv

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

SECTION 1

Introduction

The purpose of the Cornell risk assessment project was to determine the feasibility of applying risk assessment methodology to sludge management decisions. The authors conceived of this as a possible model for the larger problem of environmental risk assessment. The latter was the subject of two National Academy of Sciences reports on chemicals in the environment,^(3,4) which suggested directions for risk assessment methodology.

The risk assessment problem for environmental decision making became more prominent after the appearance of Lowrance's Of Acceptable Risk.⁽⁵⁾ It was intended to delineate the distinction between risk and safety, where risk analysis was a quantitative assessment of consequences of decisions, and safety analysis was the assessment of level of risk acceptable to society. The present authors accept that distinction, and confine themselves to risk, not safety.

A particular approach to risk assessment was published by Rowe⁽⁶⁾, distilling the results of many previous studies. This work takes the point of view that one fundamental quantity in determining risk to the populace (in the case of effects of toxic substances and in some other situations) is the degree of exposure of the populace, determined by some sort of summing of all exposures along alternate pathways by which the toxic substance reaches the populace.

BEGIN
LAST LINE
OF TEXT

The authors of the present study accept this as a basic feature, and refine it to give a methodology which, in principle, would determine what

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

proportion of the population (or what percent of the population) experiences each level of exposure to the toxic substance under some specified management strategy for handling the substance. Ideally, this would consist of charting the movements of the substance from source to final human exposure along the principle exposure paths followed by the substance, so as to allow summation of all exposure in order to obtain total exposure. This is an ideal aim, but in the presence of limited empirical data, ingenuity is required to establish approximate total exposure.

There is, however, a second part to risk analysis, even assuming that the distribution of population at each exposure level was already empirically determined. What damage does such exposure cause in terms of societal or individual losses? This is substantially the question of both: (1) establishing dose-response relations, in which the dose is the exposure level, and, (2) measuring the response either in physiological terms (e.g., organ load of a toxic substance), or in epidemiological terms (such as excess morbidity and mortality). It is only when both exposure population analysis and dosage response or epidemiological analysis are joined, that the distribution of population into levels of response can be established. At this point, safety analysis can be undertaken as the determination of whether the population response does or does not represent acceptable damage, and whether an alternative management strategy, which reduces the fraction of the population with damaging response above a certain level, is called for.

Involved in the two aspects of risk assessment are two separate categories of data requirements. The first category consists of results of carefully controlled experiments and carefully designed epidemiological statistical studies. In the case that will be taken up here (land application of sludge), such results, among others, are required for plant uptake data for cadmium in sludge, for human uptake data from cadmium in food, for animal uptake data from cadmium in grain, for physiological response data for ingestion of cadmium in food, etc. The second category of data consists of ongoing data bases which are on a national scale.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

2

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

These include both measurements of background levels of the toxic substances in the medium involved, and data on the actual levels persistent throughout the country at the many stages of the disposal and dispersal procedures. This is a massive data base requirement. Many of the results, however, would be invaluable for many risk assessment efforts other than sludge management.

Concerning the first category of data, one reason, perhaps, that the dosage response data has not been sufficiently emphasized in assessing damage, is that there is an unconscious urge to assume that the response is either proportional to the total dose received, or given by an a priori function of dose, independent of the circumstances. Two reasons that epidemiological studies of health effects have not been used extensively, are the possibility of confounding causes for observed phenomena other than those that are apparent in an uncontrolled "experiment," and the immense size of the data bases and processing effort required. Finally, it is important to stress, as others have, the fact that, very often, only the relative risks of alternate disposal plans can be estimated well, and not the absolute risks of any one. Thus, one may determine that one route will lead to many times the exposure of another, without being able to specify any one's exposure consequences very accurately.

Since there is interest in simultaneously controlling at acceptable levels all toxic substances in the environment, it is necessary to keep records for many substances at once in the national data bases. This makes the whole problem substantially multivariate and vector, rather than univariate and scalar. It complicates immeasurably the decision maker's life, since a strategy which will lower exposure to one toxic substance may very well raise exposure to another. Indeed, this is the reason no hard and fast decision rules for safety based on risk analysis (e.g., population exposure, dosage-response, epidemiological response) are likely to be forthcoming. The principal purpose of such analyses is to enlighten the decision maker as to the probable consequences in the form of response and damage that each alternative strategy will entail. The decision maker is then faced with the problem of deciding among the competing alternatives.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

3

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

Typing Guide Sheet

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

Each alternative entails resulting population exposure and population response distributions for each of 'n' toxic substances. This results in what may fairly be referred to as a vector of exposure distributions and a vector of response distributions. When specifically applied to sludge management decisions, this means that each proposed strategy for sludge disposal leads, for each toxic substance in sludge, to both a population exposure distribution and a population response distribution. A conceptualization of transmission that the authors have found informative is included as Figure 1. This both delineates the subsystems of sludge management and their interrelations, and shows how risk information in the form of probability and material distributions propagates through the subsystems.

What indeed are the ultimate disposal alternatives for sludge? Ignoring, for the purposes of this question, restrictions imposed by existing laws and regulations (which may not have any scientific basis), these are pyrolysis (incineration of some sort), water disposal (e.g., ocean dumping), and land application (including both agricultural use and simple land storage and disposal). Each alternative has advocates who cite limited information bases favorable to their view and unfavorable to others. Each alternative has well-known general advantages and disadvantages. Thus, incinerated sludge yields air pollution byproducts which impact the environment, enter the food chain, and produce health effects directly through lung respiration. Ocean dumping disturbs ocean ecosystems, the marine environment and the sea animal food chain to man. Land application and land disposal result in increased plant uptake of substances which enter the food chain to man directly through human ingestion and indirectly through use as animal fodder. It also causes toxic substances to leave application areas in runoff, entering lakes, rivers and groundwater. Each alternative yields deleterious effects to man, due to breathing, eating, or drinking toxic substances, and each alternative has its own health effects.

BEGIN
LAST LINE
OF TEXT

This has been a very brief account of the alternate disposal schemes and their obvious health consequences. It means that the decision as to what scheme or mixture of schemes to use must be influenced by the relative

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

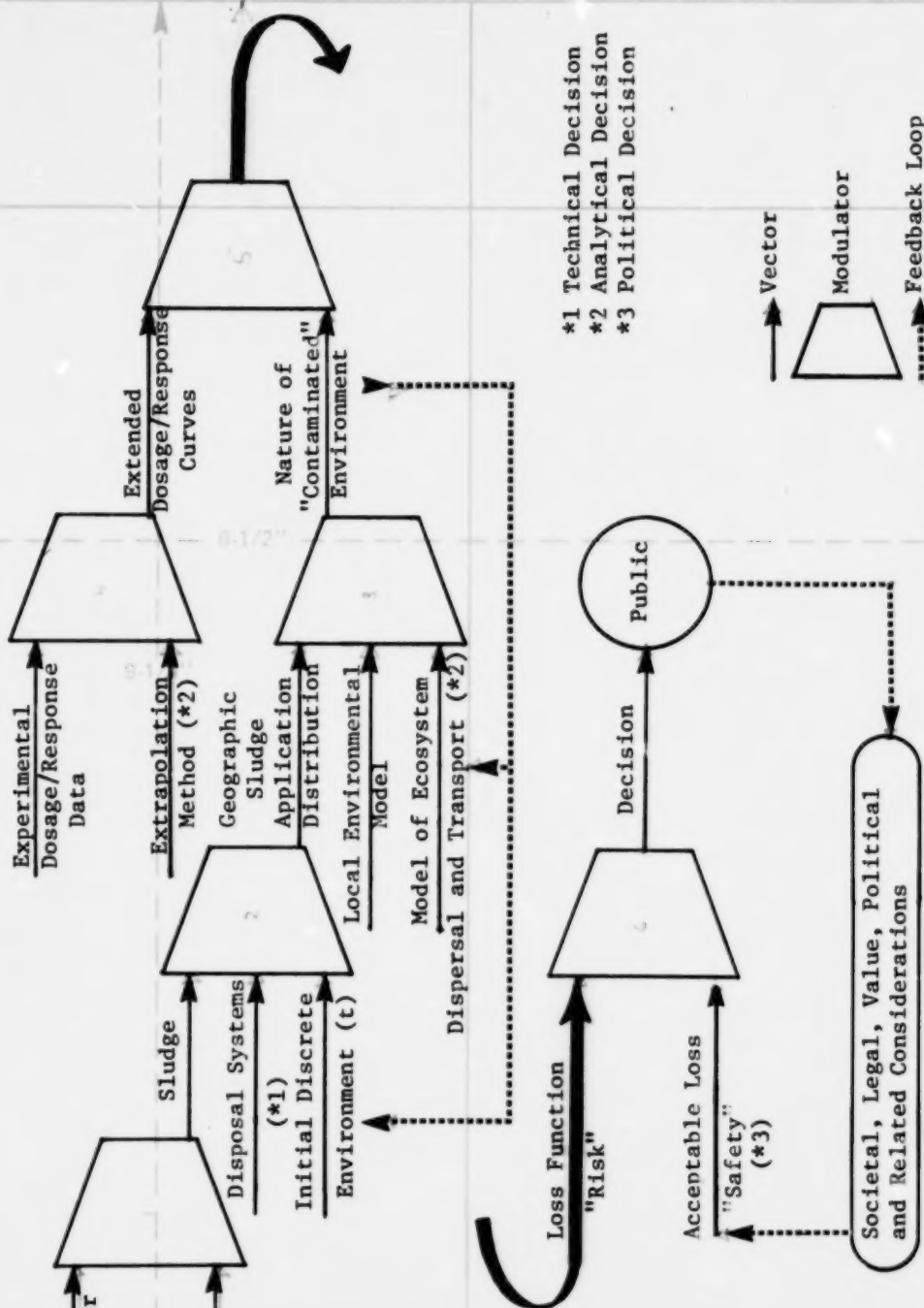
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE



- *1 Technical Decision
- *2 Analytical Decision
- *3 Political Decision

Figure 1. Preliminary Schematic Outline of Risk Assessment System

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTION'S
HERE

health effects of the different avenues of exposure on the human population. The purpose of risk analysis in sludge management, therefore, is to assess the relative effects of toxic substances on human health in the alternative disposal schemes.

In principle, this requires the establishment of population exposure distributions for each toxic substance in sludge for each disposal alternative. It requires establishment of dose-response and epidemiological results to determine the population response distributions for each health effect dependent upon each toxic substance for each alternative disposal scheme. Since population exposure depends on some kind of summing over all pathways leading to man, and each pathway involves different transport mechanisms, different transformations of form for the contaminants, different ingestion routes in man with differing efficiencies, and different physiological systems exposed to the contaminants, this is a very complicated endeavor.

The present authors restricted attention to what can be obtained from current data bases in both the literature and in computer storage systems. Since research funding constraints made it impractical to look at several toxic substances at once, it was decided to examine one important substance on which a great mass of literature has currently been assembled, cadmium in sludge. The reasoning behind this choice is that if risk assessment is feasible for any contaminant in sludge, it should be feasible for cadmium, due to the extensive attention to and many papers on cadmium in sludge. This, therefore, is a "best possible" case for risk assessment. If it is infeasible for cadmium in sludge, it is very likely to be infeasible altogether. The only blemish on this argument is that although cadmium has been decried as very harmful on general chemical grounds, in the forms that it might be ingested from sludge, very little has been done for dosage-response by way of studies to demonstrate adverse health effects. In addition, the epidemiological approach for demonstrating increased mortality, morbidity and chronic effects has not been systematically applied.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

6

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

It was decided that the best way to determine feasibility of risk assessment for cadmium in sludge was to begin an exploratory analysis of modeling, data bases, and transfer characteristics needed for an actual risk assessment. Even in this, financial constraints did not allow evaluation of data bases needed for all subsystems which enter into population exposure calculations, or evaluation of all data bases needed for the epidemiological approach to determining health effects.

As long as the object is to evaluate the effects of sludge, common questions, independent of which disposal alternative or combination of alternatives is evaluated, are: sources of sludge, measurement of cadmium content as a function of sewage plant characteristics, and output variability. This is the content of Section 5.

The risk attendant on use of any one disposal method can only be evaluated after establishment of a large reliable data base for each stage of translocation and transformation of the sludge cadmium. Since systematic risk evaluation as a subject is in its infancy, it is to be expected that some necessary data bases do not currently exist, and that those that do exist, having been accumulated for other purposes in existing measurement programs, would simply not be adequate to describe the transfer features from stage to stage of the disposal process. What can be done at present is to reanalyze these existing data bases on a single systematic basis in a form which is suitable for establishing the desired transfer characteristic for each stage and combining them to obtain a final population exposure analysis, as well as to see if it is similarly feasible to upgrade these measurement programs and to introduce new ones to fill in the present gaps, so as to demonstrate the feasibility of at least population exposure analysis for each disposal method.

The present study chose non-parametric, robust and resistant statistics, with the purpose of determining empirical distribution characterizing the desired transfer characteristics. This is illustrated in Figures 7-17 for stages I-XI of the proposed risk assessment process. What are the

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

data bases referred to that are required? Take the three methods of disposal and examine each case cursorily. In the case of land application, there is an extensive literature on soil uptake of cadmium from applied sludge and applied cadmium salts under a variety of conditions. There is also a literature on plant uptake, both as a function of soil cadmium and as a function of applied cadmium in sludge or salt form. There is a sparse literature on animal and human food uptake of cadmium from cadmium-containing food. There is a rather sparse literature on distribution of cadmium in human diets (market basket, institutional diets). There is an extremely amorphous literature on the health effects of dietary ingested cadmium.

These are the results of the activities of many scientists in many places, and were done neither on a common statistical basis nor on a transfer characteristics basis. It is necessary to reanalyze all this literature data from its raw form to obtain an insight as to whether further experiments designed to fit into transfer form for risk assessment would lead to a reliable population exposure analysis. Even the proper indicators (measurements of appropriate observable quantities) have not been standardized; these are such quantities as cadmium content of sludge, available soil cadmium, standard soils, standard definition of plant load or exposure, and standard definition of human load or exposure through dietary ingestion. This is partially due to the lack of determination of exact forms the cadmium takes, and the strong association of their effects with those of other heavy metals, and to the lack of human and animal in-vivo non-destructive testing (for which there are methodologies not yet used at the time of this report). A non-parametric reanalysis of the available data in this area has been carried out in Sections 5, 6, and 7.

To repeat, the purpose of carrying out these reanalyses is to determine whether natural refinements of present day experimental measurement practice would plausibly lead to a coherent set of transfer characteristics which, when combined, would yield, for each relevant form of cadmium, the proportion of the population with a given incremental exposure due to a given regimen of land application of sludge. Failing this, it would be

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

sufficient if enough identification of transfer characteristics would result to identify whether it is feasible to control certain stages of the sludge disposal system so as to limit the proportion of population with a given exposure level in a predetermined way at specifiabile cost. Cost, however, is wholly outside the domain of the present study.

With this done, the remaining problem would be to determine the human health effects of a given exposure level. This must either be the result of clinical trials, of extrapolation from animal experiments, or of epidemiological studies of correlation of ingestion levels with likely mortality and morbidity and chronic symptoms on a population basis. The former is far preferable to the latter, but often the epidemiological route is the only one available in exploratory data analysis, due to the lack of suitable clinical experiments. In the present case, the information on dietary distribution of cadmium available through regional market basket surveys is so inadequate in method and sample, that correlation with regional health effects is simply not possible, even on an exploratory basis. This is due to the chosen sampling technique. For the health effects of given exposure level to dietary cadmium, therefore, there is no easy solution. But current technology may be adequate to supply some dose-response information on an in-vivo basis once the usefulness of doing so has been pointed out. It should be added that past measurements of cadmium level in cadavers with given symptoms does not, so far as can be seen, contribute much information for the transfer characteristics of dose-response needed for exposure-health effect analysis for risk assessment, since the corresponding exposure levels of the cadavers are unknown.

The second sludge disposal alternative, pyrolysis, has a missing data base at an earlier stage: analysis of the pyrolysis air products of sludge and the variability thereof. No adequate studies have been done. However, from the corresponding results for other substances such as coal, it is natural to guess that much of the available cadmium in sludge will persist on the surface of small particulate matter in the air even after severe cleansing measures have been taken. It is thus very reasonable, since much

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

9

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

of the cadmium currently in air arises by a pyrolysis of similar character, to see whether health effects of the air cadmium can be obtained either by clinical testing (health effects of smoking studies are basic here for methodology), or by epidemiological correlation of air cadmium levels throughout the country with disease-specific mortality rates as derived from causes of death on death certificates. For the respiratory ingestion of cadmium, a recently reported in-vivo testing procedure used in a smoking study, (reference 7) appears capable of measuring some desired dose-response characteristics, i.e., body burden of cadmium. The authors see this as indicating that an in-vivo testing method for dose response from air cadmium and other heavy metals is now feasible, but has only been performed marginally for smoking as a source of air cadmium. This could not be quantitatively pursued without undertaking actual experiments.

The other route available for estimating the health effects of air cadmium is the epidemiological one. For this one, information is available in two data banks: one, the census reports of cause of death as reported on death certificates county by county, the other, the air cadmium levels recorded in the National Aerometric data Base. An exploratory non-parametric univariate analysis was carried out to determine if there was association between air cadmium level and nephritis and nephrosis (NEPH), Hypertension (HYPERT), and hypertension with or without renal failure (HYPER). The authors believe that this analysis indicates that clinical studies of the association (and far larger multivariate nonparametric studies of association with many air measurements of other heavy metals) is needed to determine whether the relation is causal or merely due to confounding omitted factors. Under the charge of the present study, which limits it to sludge management risk assessment, the sole purpose of the air cadmium analysis is to determine if present technology and data bases will reveal the effects of pyrolysis of sludge; this would form an essential step of such analysis in the absence of non-destructive clinical testing. If, however, such association is investigated further, it would possibly be of importance in other pyrolysis problems, including coal burning.

BEGIN
LAST LINE
OF TEXT

3/8"

10

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

There remains as a basic alternative, ocean dumping. This is being phased out by federal regulation at present, but of course the existence of the regulation does not prove that the risks attendant upon ocean dumping are worse than the risks attendant on other alternatives. Rational analysis and justification of regulation demands that this alternative be explored just as the other two should be explored. The most apparent effect of ocean dumping is shellfish and fish uptake of cadmium. Although this has been studied, there are no studies that the authors have found on the result of exposing fish to dumped sludge, with measures, for example, of the cadmium content of the sludge, aquatic environment, and subsequent uptake by fish. Thus the contribution of dumped sludge to the human food chain is to a large extent an uncharted area.

There were two further studies undertaken but not reported here. One concerned water and the other concerned ecosystems. Brief descriptions follow.

There is a subsidiary effect of land application, namely cadmium in groundwater and cadmium in runoff. The former lacks a good data base and is notoriously local in character. There is a national Watstore data base in the Environmental Protection Agency's Storet system. The authors attempted to carry out a study based on cadmium readings in water in the various river basins in the United States, which could be synthesized from the Watstore individual measurement bank. Unfortunately, the data base is too thin per basin, when sorted by rudimentary quality of measurement criteria, to allow a decent "cadmium map" of any significant water basins, and thus the correlation of water basin characteristics with either health effects or runoff from agricultural lands or from geological formations was thwarted. This study has been omitted from the final report, although a complete paper copy of the cadmium river basin maps for the United States is on file at Cornell.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

The authors were interested also in the ecosystem effects of toxic substances on the distribution of species, for which a compartment model seemed suitable. The existing literature on the ecological effects of cadmium was abstracted and catalogued. A synopsis of the resulting file data indicated that, for the purposes involved, the literature was highly skewed as to the organisms that have been studied. The skew favors fish and crop plants. These are the only categories of organisms which were sufficiently well represented in the literature to make even a token application of a compartment model possible. What is required is sufficient statistical data on trophic dynamics and epidemiological response, and only for fish and crop plants was such data found. A serious study of ecological dynamics for land application or ocean dumping depends on more direct scientific studies of dynamics and response for other appropriate species. This type of compartment modelling for real data, therefore, is not presently justified. The data files are available at Cornell and are not reproduced here.

8-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

12

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 2

Conclusions

On the basis of the analysis it appears feasible to use risk assessment for decision making on toxic substance disposal. In particular, in the case of sludge applied to agricultural land, it appears feasible to carry out population exposure analysis for cadmium and other heavy metals. The full assessment of risks, however, entails evaluating population (health effects) response, and calls for further research of a fundamental character in the area of dosage-response. It is also necessary to formulate record keeping protocols and to mandate record keeping of an extensive character at every stage of the disposal process.

The size of the required data base for toxic substance risk evaluation appears to be of the same magnitude and expense as those for national econometric models. The situation is analogous to that of national econometric models in the 1940's. At the time, they were regarded as impractical or hopeless, due to the necessity of ongoing collection of many data bases for every stage of the economy. Forty years later these bases are routinely mandated, kept, improved, and used. Many of these bases serve multifold purposes for the public and private sectors, and act as descriptions of subsystems of many different economic entities. The situation for population exposure analysis for dispersed toxic substances, as in sludge, is quite similar. The records required for exposure analysis are very extensive, and almost all should be collected with a protocol which would allow their use for exposure analysis for many toxic substances arising from sources other than sludge.

BEGIN
LAST LINE
OF TEXT

3/8"

13

PAGE NUMBER

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

The whole process of risk assessment should, therefore, be thought of as depending on data bases useful for many different exposure analyses. As the tools of statistics and modelling develop, clearer and more precise versions will be revealed.

A standard engineering criticism of population exposure modelling is that the mathematical equations governing transmission, translocation, and transformation of the substances involved are in many cases unknown, and if known involve so many special constraints dependent on local conditions, that they are useless. This is entirely true, but it does not vitiate exposure analysis, which is to a certain degree quite independent from such detailed information on cause and effect.

The econometric analogy is valuable here. The same objection can be made equally well to national econometric models, but the reply is the same for both cases. Crude macroscopic models (such as input-output models in economics or the distribution models proposed in this report often give fair information exactly because they summarize information which, when massed properly, is intelligible and stable and has practical content, but where the actual phenomena involved are governed locally by unknown exact equations or chance phenomena. It may finally be argued that however cumbersome and unwieldy the population exposure base may seem, it will eventually be accumulated anyway as regulators and industry realize that the only way to defend the prudence of their decisions in a rigorous way is through such exposure analysis, using best current data and risk analysis.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 3

Recommendations

1) Risk assessment for sludge management should assess comparative population exposure and health effects obtained for each of the main sludge management alternatives: land application, incineration, and ocean dumping.

6-1/2"

2) Risk assessment for these alternatives in sludge management is best carried out in the context of a general risk assessment program for heavy metals and probably for toxic substances. The many necessary data bases for each risk assessment for sludge management are certain to be used as subsystem descriptions for risk assessments for other toxic substance management problems not involving sludge management.

3) The empirical distribution of the nation's sludge output, characterized by heavy metal levels, needs to be collected on an ongoing basis. A record keeping and reporting system should be mandated.

Exploratory data analysis on preliminary data indicates that the monitoring resources should be utilized to maximize the number of plants sampled, rather than the number of times a single plant is sampled.

4) The distribution of land area by yearly application rate of sludge needs to be evaluated by sampling, together with descriptions of land type and crop. The result is the cadmium loading pattern. Exploratory data analysis reveals that it is likely that cadmium availability for

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
LAST LINE
OF TEXT

3/8"

15

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

plant uptake depends on recency of application. Expressed in another way, the time pattern of application will actually alter the uptake rates and plant levels.

In particular, it appears that the primary determinant of plant uptake rate is the amount of cadmium applied in the two or three years immediately preceding the harvest year. This possibility should be investigated as a potential control point in the land use strategy; it should certainly be incorporated as a design element in any future studies of plant uptake following sludge application. Soil type is important as well.

5) For a variety of plants (corn, soybeans, etc.) the relative proportion that each one accounts for in the mix of crops that will be grown on sludge-amended soil should be ascertained, as should the distribution of cultivars within species. The analysis should be separated at this point by plant type.

6) From existing data and from new work, as required, the response (uptake and translocation) of these cultivars and species needs to be found, or a plausible distribution of such responses needs to be estimated, and the resulting distribution convolved with the one described in recommendation 4, the cadmium loading pattern. One may now imagine that the problem has been refined to that proportion of the whole cadmium problem that is represented by the fraction of the total acreage that is devoted to the particular cultivar.

7) The distribution should then be refined further by plant part, and the task here is simply to keep track of the separated distributions of uptake in leaf, grain, and stover.

8) Population physiological and epidemiological response to dietary cadmium exposure has not been established by current research. This is a necessary component of risk assessment if the latter is to be based on population response, rather than population exposure.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

16

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

9) The measurements needed for the forms of cadmium at each level of the risk analysis process have not been standardized. This is essential for uniformity and reliability of results. This is the problem of validating the indicators of risk.

10) The data bases are not organized nationally so as to facilitate population exposure analysis, i.e., exposure to cadmium via air, food and water. Thus programs for accumulating the missing bases, and programs for rationally storing the bases in compatible form need to be developed.

11) It is desirable to collect the bivariate distributions expressing the dependencies of pairs of variables (assumed to be independent in the stage diagrams) as well as the marginals of these distributions described above, at least for all heavy metals.

12) The statistical methodology for estimating distributions that result from the combinations used for population exposure analysis from sampled data for the component distributions should be developed further. The non-parametric approach appears to be best suited mathematically for this purpose.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

17

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

SECTION 4

Methods: The Application of Distribution Models to Risk Assessment
in Sludge Management

Introduction

Figure 1 illustrates the authors' first attempt at developing a methodology for risk assessment in sludge (1977). The idealized subsystems of movement of any toxic substance through the environment are given abstractly in Figure 2. The alternative disposal routes for sludge are represented in Figure 3. The points in the disposal process where control of the level of toxic substances can be exercised are in Figure 4. The methods of control available at these control points are given in Figure 5. The agents which are in a position to exercise such control potentially are listed in Figure 6. In Figure 7 for land application of sludge the route to human health effects is pictured, including stage numbers as used in this report. The distribution model methodology follows next.

BEGIN
LAST LINE
OF TEXT

3/8"

18

PAGE NUMBER

EPA-287 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Source 1.....Source 2

Environmental
Distribution of
Toxic Substance
in Space and Time

Environmental
Distribution of
Organisms
in Space and Time

Distribution in
Space and Time of
Physical Changes in
the Environment

Distribution in
Space and Time of
Exposures of
Organisms

Distribution in
Space and Time of
Effects of Degradation
of Environment

Distribution in
Space and Time of
Physical Changes in
Organisms Due to
Exposure

Distribution in
Space and Time of
Ecological Effects

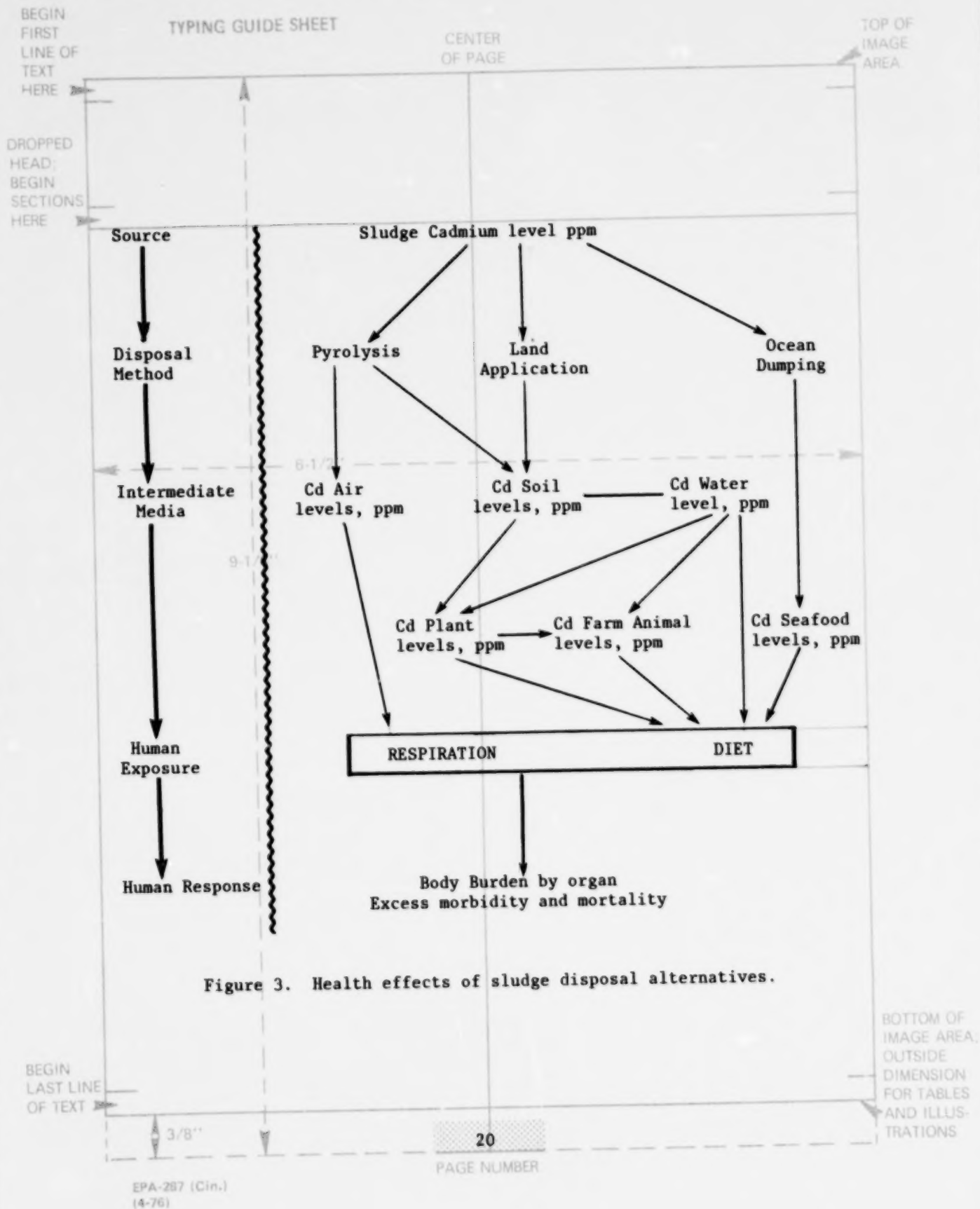
Distribution in
Space and Time of
Health Effects

Figure 2. Idealized subsystems in the pattern of entry, movement, and consequences of a toxic substance in the environment.

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
LAST LINE
OF TEXT

3/8"



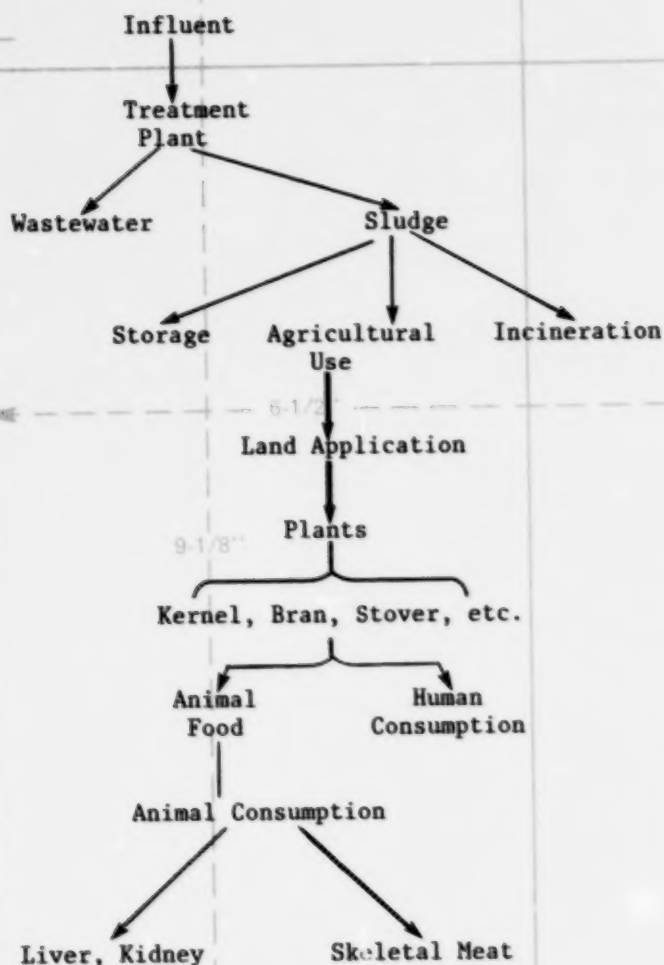
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE



1. Sources
2. Process in Treatment Plant
3. Output Choices
4. Application Program
5. Planting Schedule
6. Choice of Planted Crop
7. Processing of Crop
8. Disposition of Crop
9. Animal Consumption
10. Surveillance

Figure 4. Points for control in sludge management.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN FIRST LINE OF TEXT HERE	TYPING GUIDE SHEET		CENTER OF PAGE	TOP OF IMAGE AREA
DROPPED HEAD: BEGIN SECTIONS HERE	¶	Curtail or detour sources of cadmium to the influent stream.		
	¶	"Fix" cadmium, either by additions or changes in treatment sludge.		
	¶	Output choices include cadmium to wastewater or dewatered sludge.		
	¶	Deposition of the sludge includes agricultural uses, reclamation of marginal or "spoil" land, stockpiling, isolation, incineration and ocean dumping.		
	¶	Land application changes include planting schedule, rotation and "banking" of land, site-selection, soil management.		
	¶	Choice of crops.		
	¶	Disposition of crops, animal food, human consumption and non-agricultural purposes.		
	¶	Processing of crops, milling and separation, selective use of plant products.		
	¶	Animal consumption, selective choice of species, animal part, ultimate disposition.		
	¶	Surveillance.		
BEGIN LAST LINE OF TEXT	Figure 5. Methods of control in sludge management.			BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUS- TRATIONS
	3/8"	22		
	PAGE NUMBER			
	EPA-287 (Cin.) (4-76)			

BEGIN FIRST LINE OF TEXT HERE

TYPING GUIDE SHEET

CENTER OF PAGE

TOP OF IMAGE AREA

DROPPED HEAD; BEGIN SECTIONS HERE

1. Sources: Federal, state, municipal, or industrial.
2. Treatment process: Municipality; financial incentives or regulatory control by state and federal agencies.
3. Output choices: Same as 2.
4. Deposition program: Same as 2.
5. Planting schedule: Not likely to be under central control except in cases in which a municipality engages in or contracts agriculture, or uses some or all sludge in non-agricultural applications.
6. Choice of crops: Same as 5; stringent control efforts would probably hamper acceptance.
7. Processing: No central control, option of farmer. Government recommendations possible.
8. Animal consumption: No central control, option of processor.
9. Surveillance: Governmental responsibility.

Figure 6. Agents for exercise of control in sludge management.

BEGIN LAST LINE OF TEXT

3/8"

23

PAGE NUMBER

BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

EPA-287 (Cin.)
(4-76)

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Report Reference

Cadmium Content of Sludge

Stages I, II
(Figures 8, 9)

Sludge Production

Application Rates

Stages III, IV
(Figures 10, 11)

Land Application

Exposure of Crop to Cadmium in
Soil,

Stages V, VI
(Figures 12, 13)

6-1/2"

Crop

Mix of Varieties, Cultivars,
Soil Types, etc., Site
Selection

9-1/8"

Stages VII, VIII
(Figures 14, 15)

Crop Use
Pattern

Cadmium Levels of Plant Material

Direct Human Consumption
Animal Feed, Composting,
etc.

Human Exposure Pattern

Stages IX, X
(Figures 16, 17)

Human Uptake
System

Variable Efficiency of
Uptake from Food

Stage XI
(Figure 18)

Human Exposure

Human Response

Figure 7. Health effects from land application of sludge.

BEGIN
LAST LINE
OF TEXT

3/8"

24

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

The system diagram and simplest mathematical distribution model for exposure analysis for human population of exposure to cadmium from land application of cadmium-bearing sludge, uptake of cadmium by plants, and human ingestion of grain crops through the diet, will be given in stages labelled I through XI (Figures 8-18). It must be emphasized that these Figures are oversimplified for legibility, and that a more comprehensive treatment is given below for Figures 8-15. This is to be regarded as the authors' recommended analysis of such problems, but a complete analysis involves similar analysis for every major exposure pathway and a summing of all such exposures by the appropriate mathematics to obtain total exposure. Also, once such total exposure is obtained, there still remains the separate problem of determining acceptable exposure levels through dosage response and epidemiological research and level of safety tolerable by society.

Stage I.

The first stage is application of sludge with concentration c ppm Cd (c parts per million cadmium) at an application rate of a metric tons per hectare yearly (aMT/ha), resulting in cadmium load rate $L = ac$ grams per hectare. If both the cadmium concentration and the application rate a were constant and known, then L would be constant and known. But c is a variable quantity varying both with sludge sources and sludge processing, and a is a variable quantity based on land application patterns, which themselves are based on agricultural regulatory and economic constraints. The basic item for modelling and measurement is $h(a, c)$, the percent frequency distribution of hectares of sludge amended crop land for human consumption with a as application rate and c as concentration. This bivariate distribution is not currently being sampled in any systematic way, and requires additional record keeping programs beyond those presently in existence. Its evaluation depends on sampling sludge cadmium concentration from many plants and sampling application rates over crop sludge applied land, together with the appropriate levels involved and the hectares involved, for each crop cultivar. This presents problems of record keeping design, but no major scientific measurement problems beyond those of proper measurement of cadmium in

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

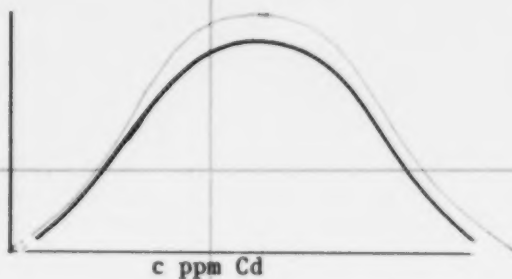
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

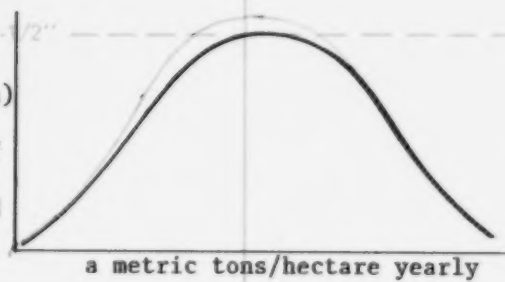
DROPPED
HEAD;
BEGIN
SECTIONS
HERE

$f(c)$
% of
Sludge



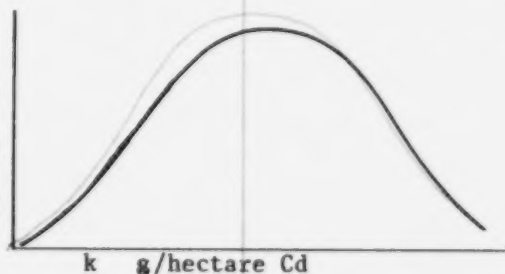
Percent distribution of cadmium concentration in sludge,
and

$h_1(a)$
% of
land



Percent distribution of land at each yearly application rate,
yield

$L(k)$
% of
Land



Percent distribution of land at each year cadmium loading rate.

BEGIN
LAST LINE
OF TEXT

Figure 8. Stage I.

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8''

26

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

sludge. Note that regulations, economics, and political pressures can enforce regions of (a, c) where $h(a, c)$ is negligibly small by requiring that c is below a fixed limit (concentration limit), or that a be less than a fixed limit (application rate limit), or that ac be less than a fixed limit (loading rate limit). How is the variability of a, c related to $h(a, c)$?

The two input distributions in the figure for stage 1 are $f(c)$, the frequency distribution of sludge at each concentration level c ppm, and $h_1(a)$, the frequency distribution of land at each application rate a metric tons/hectare. The single output distribution in the figure for stage 1 is $L(k)$, the frequency distribution in percents of land with k grams/hectare cadmium yearly application rate. Then

$$h_1(a) = \int h(a, c) dc,$$

$$f(c) = (A/T) \int ah(a, c) da$$

(from now on all quantities are non-negative and all integrals are from zero to infinity). A is the grand total of application area, T is the grand total of sludge applied altogether. Further note that

$$L(k) = \int h(a, k/a) da.$$

Without further simplifying assumptions, therefore, the frequency distribution of sludge applied land at k grams/hectare yearly application rate must be computed directly from the bivariate distribution $h(a, c)$ (and can not generally be computed from $h_1(a)$, $f(c)$). The figure for stage 1 deals with the simplified case when a , c are independent of one another, that is application rate is independent of concentration. In this simplified case, with $h_2(c) = \int h(a, c) da$, we have marginals h_1 , h_2 for h and the independence assumption says $h(a, c) = h_1(a)h_2(c)$. Of course $h_2(c)$ is the distribution of sludge applied land at concentration c of cadmium in applied sludge. To proceed further, introduce $s(a, c)$, the frequency distribution of sludge applied at rate a , concentration c . The relation (area of application times application rate equals total sludge applied) yields

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

$$(Ah(a,c)\Delta a\Delta c) a = Ts(a,c)\Delta a\Delta c, \text{ so}$$

$$Aah(a,c) = Ts(a,c).$$

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Note integration gives

$$A \iint ah(a,c)dada = T \iint s(a,c)dadc, \text{ or}$$

$AE(a)$ = expected value of application rate = T , $E(a) = T/A$, as is obvious anyway. Integration also yields as marginals for $s(a,c)$

$$s_1(a) = \int s(a,c)dc = (A/T) \int ah(a,c)dc = (aA/T) \int h(a,c)dc$$

$$s_2(c) = \int s(a,c)da = \int (A/T)ah(a,c)da = (A/T) \int ah(a,c)da$$

and conversely as marginals for $h(a,c)$

$$h_1(a) = (T/Aa) \int s(a,c)dc = (T/Aa)s_1(a)$$

$$h_2(c) = (T/Aa) \int h(a,c)dc = \int (T/A)s(a,c)(da/a)$$

$$= (T/A) \int s(a,c)d\log a.$$

When a, c are independent, and $h(a,c) = h_1(a)h_2(c)$, since $s(a,c) = (A/T)ah(a,c) = (Aa/T)h_1(a)(h_2(c))$, the first factor depends only on a , the second only on c , and get $s(a,c) = s_1(a)s_2(c)$. From the two representations of $s(a,c)$ we get

$$((Aa/T) \int h(a,c)dc)((A/T) \int ah(a,c)da) =$$

$$((Aa/T)h_1(a))(h_2(c)).$$

So finally $h_2(c) = h(a,c)da = (A/T) ah(a,c)da f$, so f is in fact the marginal h_2 . So when a,c are independent,

$$L(k) = \int h_1(a)h_2(k/a)da = \int h_1(c)f(k/c)dc.$$

Thus in the case concentration and application rate are independent of one another the indicated integration of $h_1(a)f(k/a)$ yields $L(k)$. This is

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

precisely the result indicated by the figure for stage 1, with h_1 , f as inputs and $L(k)$ as output. In the unsimplified case $L(k)$ must be obtained from $h(a,c)$ directly, and hence depends on the extensive data collection program required to estimate $h(a,c)$ from empirical data. Data collection for h_1 , f would of course be simpler but less reliable.

(It is worth noting in conclusion of the discussion for stage 1 that this and other computations can also be obtained by using the statistician's method of the calculus of distributions of random variables. But this is somewhat misleading, since the theory of random variables is always interpreted in terms of indefinitely repeatable experiments while the above computations are really for physical mass distributions, which is an old but mostly nonstatistical interpretation of the notation for random variables. Since the latter are thus subject to rampant misinterpretation in this context, that language has been avoided in favor of old fashioned computation.)

Stage II.

Stage I had as its end product the frequency distribution $L(k)$ of sludge applied land area at yearly cadmium loading rate k g /hectare. With this as input the figure for stage II has as output the frequency distribution $\bar{L}(i)$ of sludge applied land area at level i ppm of incremental yearly soil cadmium. Assuming i is determined by k and conversely (that is, that cadmium loading rate determines incremental soil cadmium and conversely), one gets

$$L(k)dk = \bar{L}(i)di, \text{ or}$$

$$L(k(i))(dk/di) = \bar{L}(i).$$

The simplest useful model is linear dependency, a common assumption, which then yields $k = \alpha i$, α a soil dilution factor from experiment. This yields the relation

$$\bar{L}(i) = \alpha L(\alpha i),$$

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

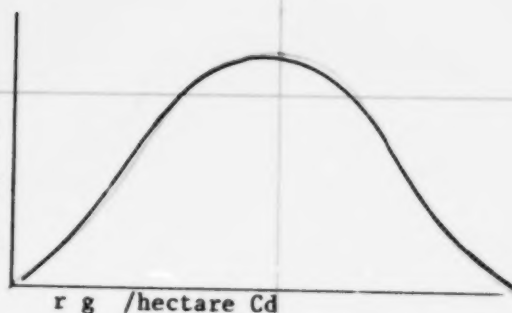
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

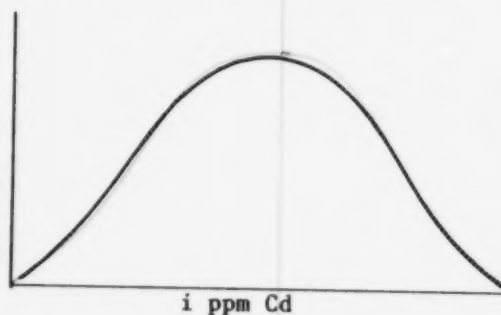
$L(r)$
% of
land



Percent distribution of land at each yearly loading rate
yields

6-1/2"

$\bar{L}(i)$
% of
land



Percent of land at each incremental yearly soil cadmium concentration.

Figure 9. Stage II.

BEGIN
LAST LINE
OF TEXT

3/8"

30

PAGE NUMBER

EPA-287 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

a simple scale change. The next more elaborate model would make i a function of the differing k for several preceding years.

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Stage III.

The figure for stage III has as its input $\bar{L}(i)$, the frequency distribution of sludge applied land at incremental yearly soil cadmium level i ppm. The figure for stage III has as its output the corresponding distributions for each crop t separately. That is, the output is $\bar{L}_t(i)$, the distribution of sludge applied land to grow crop t at incremental yearly soil cadmium level i ppm (due to sludge application). Thus what is required is to split the land application area by crop use. This is in fact a record keeping requirement, imposed on stage I, with information picked off at stage III. Going back to the distribution $h(a,c)$ of stage I, what must be obtained for each crop t is in fact $h_t(a,c)$, the frequency distribution of sludge applied land devoted to crop t with sludge application rate a , concentration c . When stage I and stage II computations are then applied to each h_t separately, the desired $\bar{L}_t(i)$ distributions may be computed, as outputs for stage III.

Stage IV.

Stage IV represents the transfer of incremental soil cadmium (yearly, measured as i ppm) to plant cadmium (measured as r ppm of total plant). The incremental yearly soil cadmium resulting from the previous year's sludge application is a simplified present predictor of plant uptake suitable only as an example, and this is what is intended here. There are two inputs to stage IV. One is the output of stage t for crop t , namely the distribution $\bar{L}_t(i)$ of land which is sludge applied the previous year and used to grow crop t in the present year. The other input is the distribution of crop t cultivar uptake efficiency e , call it $E_t(e)$. This is to be determined by agricultural experiment. The output $U_t(r)$ from stage IV is the distribution in percents of crop t at each uptake rate r in ppm Cd. The simplified model of uptake is of course $r = ei$, where i is the incremental soil cadmium from last year's land application of sludge, e is the efficiency uptake factor, and r is the uptake rate. Let $E_t(e,i)$ be the

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
LAST LINE
OF TEXT

3/8"

TYPING GUIDE SHEET

BEGIN
FIRST
LINE OF
TEXT
HERE

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

$\bar{L}(i)$

% of
land

i ppm Cd

Percent of land at each incremental yearly soil cadmium concentration.

8-1/2"

9-1/8"

$\bar{L}_1(i)$
% of land
for
Crop 1

i ppm Cd

$\bar{L}_k(i)$
% of land
for
crop k

i ppm Cd

Percent of land at each incremental yearly soil cadmium concentration split by crop use.

Figure 10. Stage III.

BEGIN
LAST LINE
OF TEXT

3/8"

32

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

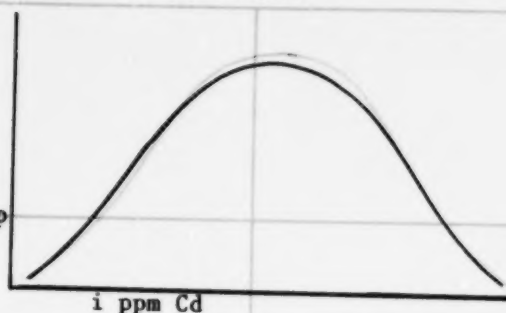
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

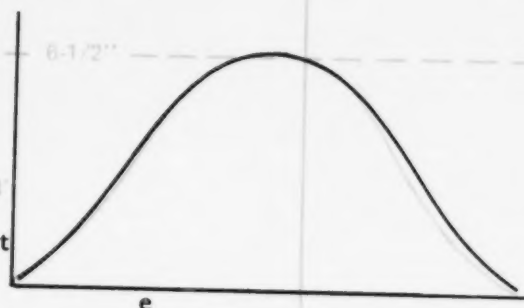
$\bar{I}_t(i)$
% of Crop
t



Percent of land at each yearly incremental soil cadmium concentration for crop t.

and

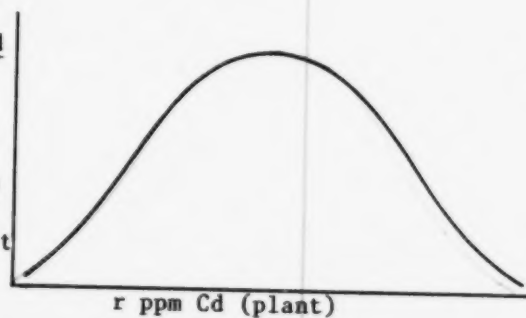
$E_t(e)$
% of
Crop t



Percent of crop t at each uptake efficiency for crop t

yield

$U_t(t)$
% of
Crop t



Percent of crop t at each uptake rate.

Figure 11. Stage IV.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

bivariate distribution of crop t according to efficiency levels e and yearly incremental soil cadmium i from last year. This is the underlying distribution, whose tabulation or sampling would be feasible but difficult, and not the result of simple agricultural experiment if e, i are dependent. In terms of the governing underlying distribution $E_t(e, i)$ one obtains $U_t(r) = \int E_t(e, r/e) de = \int E_t(i, r/i) di$. Here the marginal distribution $\int E_t(e, i) di$ is the distribution of sludged crop t by efficiency level e , that is $E_t(e)$. In case uptake efficiency is independent of incremental cadmium level, the same calculation as for stage I shows that

$$U_t(r) = \int \bar{L}(i) E_t(r/i) di = \int \bar{L}(r/e) E_t(e) de,$$

and the output of stage IV has been obtained from the inputs. It is to be noted that in stage IV the simplified diagram of the figure for stage IV and the calculation just made for the independent case must be supplemented, since a high enough soil cadmium level is often correlated with factors which destroy the crop (and eliminate efficiency of uptake). Furthermore, the above computations need to be modified to take into account the findings of Section 7, i.e., that plant cadmium uptake is a function of the recency of sludge application.

Stage V.

The input is for each crop t , the distribution $U_t(r)$ of crop t into cadmium uptake rate r in ppm. The output of stage V is for each crop t , the distributions $U_{t\ell}(r)$, $U_{tg}(r)$, $U_{ts}(r)$ of leaf, grain, and stover in crop t to cadmium uptake levels r ppm. The simplest linear model, grain (or other edible components) concentration = α_{tg} times total plant concentration, etc., gives $U_{tg}(r) = (1/\alpha_{tg}) U(\alpha_{tg} r)$, etc. More complex dependencies can easily be modelled if necessary. So the output of stage V used below is the distribution $U_{tg}(r)$ of grain in crop t grown on sludged land in grain cadmium uptake levels.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

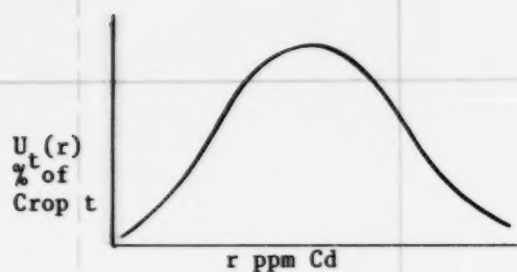
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

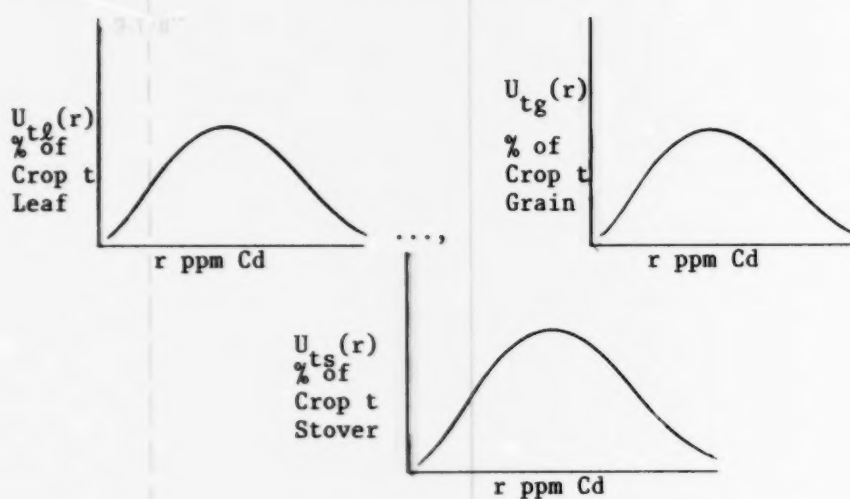
CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE



Percent of crop t at each uptake rate.



Total crop t uptake split by plant part.

Figure 12. Stage V.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

35

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Stage VI.

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Stage VI deals with sludged grain from crop t vis-a-vis non-sludged grain from crop t . From stage V above, one has as one input in the figure for stage VI the distribution $U_{tg}(r)$ of sludged grain crop t at each cadmium level r ppm Cd (grain). But there is also a distribution $V_{tg}(r)$ of unsludged grain crop t into (unsludged, or not sludged last year) cadmium levels r . The latter distribution is of course to be estimated by sampling unsludged grain crop t for its cadmium level. An important strategy for calculating incremental human dietary exposure due to sludge application is to separate these distributions, and carry out the succeeding calculations separately for both, and to compare the magnitudes of the resulting dietary exposures. What is lacking then is a description of the mix of sludged and non sludged grain crop t that after marketing is used for human dietary intake. This is a very difficult sampling problem due to the complexity of the distribution network. An attack which seems plausible to this problem is a "worst case analysis," based on the assumption that there is no mixing whatever of sludged with nonsludged grain, and that these two distributions are used wholly separately as food stuffs. (The sense in which this may be regarded as a worst case is complex. One aspect is that this says no direct dilution of high cadmium sludged grain is allowed by the unsludged. Another is that in several senses the resulting total distribution has as much scatter as any case with mixing. See below.)

Assume that there is no mixing, and that the sludged and unsludged grain reach the diets unmixed. This is the subject of the figure for stage VI. How is $w_{tg}^{UM}(r)$, the distribution into percents of unmixed total grain crop t into cadmium levels r to be computed from $U_{tg}(r)$ the sludged grain crop t distribution and $V_{tg}(r)$ the unsludged grain crop t distribution? One obtains

$$w_{tg}^{UM}(r) \quad \gamma_t U_{tg}(r) = (1-\gamma_t) V_{tg}(r):$$

where $\gamma_t:1-\gamma_t$ is the ratio of sludged grain crop t to unsludged grain crop t .

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

36

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

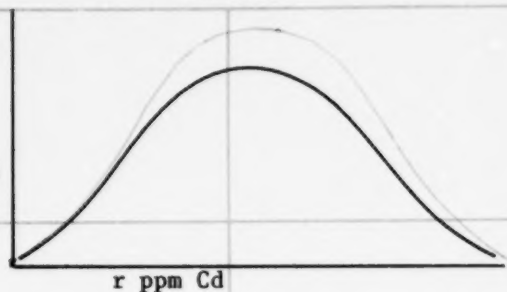
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

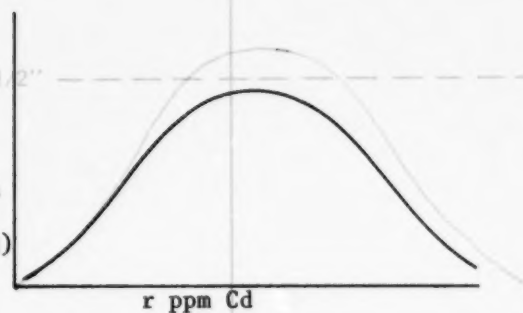
$U_{tg}(r)$
% of grain
Crop t
(sludged)



Percents of grain crop t at each cadmium concentration (sludged)

and

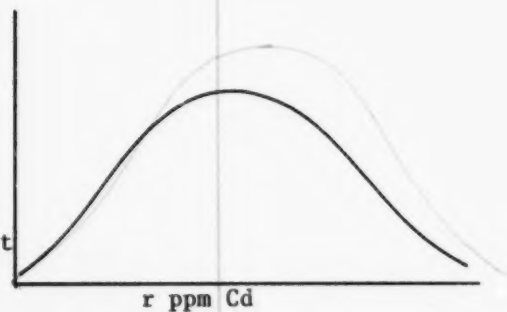
$V_{tg}(r)$
% of grain
Crop t
(unsludged)



Percents of grain crop t at each cadmium concentration (unsludged)

yield

$W_{tg}^{UM}(r)$
% of total
grain crop t



Percents of total grain crop t at each cadmium concentration (unmixed case).

BEGIN
LAST LINE
OF TEXT

Figure 13. Stage VI.

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Why should this be regarded as a "worst case"? The food distribution system and dietary habits result in a partial mixing, giving $W_{tg}^{PM}(r)$ dependent on the exact distribution system, quite hard to estimate by sampling. Then it may be seen that the expected value of cadmium level r in grain crop t is unchanged whether there is partial or total or no mixing, that is in all cases the expected value is

$$\int r W_{tg}(r) dr = \gamma_t \int r U_{tg}(r) dr + (1-\gamma_t) \int r U_{tg}(r) dr$$

that is, it is γ_t times expected sludged value plus $(1-\gamma_t)$ times unsludged expected value, next, it can be seen that the absolute deviation $\int r - r_* W_{tg}^{PM}(r) dr$ of the partially mixed case is for any r less than or equal to the absolute deviation $\int r - r_* W_{tg}^{UM}(r) dr$ of the unmixed case. Finally, the squared deviation $\int r - r_*^2 W_{tg}^{PM}(r) dr$ of the partially mixed case is less than or equal to the squared deviation $\int r - r_*^2 W_{tg}^{UM}(r) dr$ of the unmixed case. So in general the scatter features are "worst possible" for the unmixed case. This tends to be evidence that the procedure for the unmixed case is a reasonable one in the lack of sufficient surveying of direct dietary habits and distribution systems for grain crops.

Stage VII.

The figure for Stage VII is intended to have as inputs the distribution of total grain crop t at each cadmium concentration used for direct human consumption, and also the distribution $Y_{tg}(r)$ of the population ingesting r g /day of grain crop t . The output is supposed to be the distribution $\phi_{tg}(z)$ of percents of the total population ingesting $z \mu g$ /day cadmium from grain crop t . This transformation from inputs to outputs is again a simplified case. The governing bivariate distribution is $k_{tg}(c, r)$, the distribution of population which ingests r g /day of crop grain t which grain has concentration $c \mu g$ /day. This is again a sampleable distribution. At this point it should be said that the distributional mathematics of feeding grain to people coincides with the distributional mathematics of feeding sludge to plants, and the same computations as for Stage I now gives

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

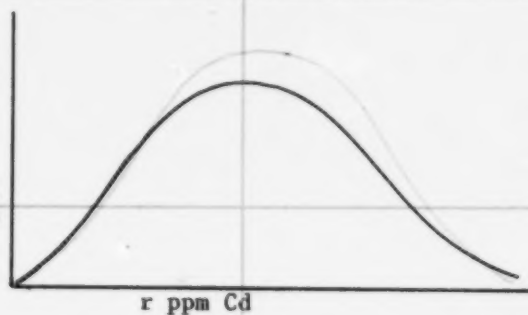
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

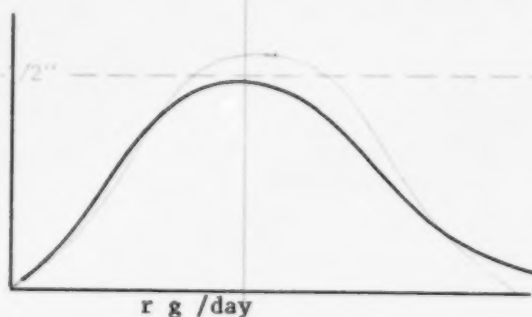
$W_{tg}^{UM}(r)$
% of total
grain crop
 t



Percents of total grain crop t at each cadmium concentration (unmixed cases)

and

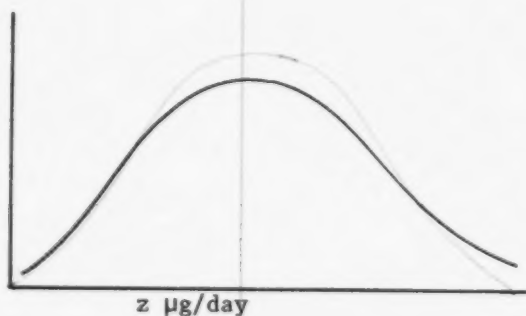
$Y_{tg}(r)$
% of total
Pop



Percents of total population ingesting r g /day grain from crop t

yield

$\phi_{tg}(z)$
% of total
Pop



Percents of total population ingesting z μ g/day cadmium from crop t .

BEGIN
LAST LINE
OF TEXT

Figure 14. Stage VII.

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

$$\phi_{tg}(z) = \int k(c, z/c) dc = \int k(z/r, r) dr.$$

If independence of dietary intake from cadmium concentration c is assumed, one gets $W'_{tg}(c) = \int ck(c, r) dc =$ distribution of grain t into cadmium concentration levels $c \mu g/day$. Then $Y_{tg}(r) = \int k(c, r) dc =$ distribution of population into intake rates r , and $\phi_{tg}(z) = W_{tg}(c) Y_{tg}(z/c) dc$. Now $W'_{tg}(c)$ is obtained from $W_{tg}^{UM}(r)$ with the unmixed assumption from stage VII by a scale change, $r = \beta c$, giving as for stage 2 $W'_{tg}(c) = \beta W_{tg}^{UM}(\beta c)$, that is in the case that ingestion rate and concentration are independent, one gets

$$\phi_{tg}(z) = \beta \int W_{tg}^{UM}(\beta c) Y_{tg}(z/c) dc$$

as the output of stage VII.

Certain notes are in order. First, the above mentioned independence is clearly violated by such cases as milorganite gardeners who are vegetarians and subsist on the products of their own plots.

Second, as was mentioned before, only the grain directly consumed by humans has been accounted for. The great amount fed to meat animals, and thence to humans, is outside the particular food chain that the figures are discussing. However, the grain crop t can be split by entity fed (type of animal), then the animal ingestion has a certain efficiency, then the ingested cadmium is split by tissue and organ in which deposited, then the tissues have distributions for dietary use by man. This is wholly similar to the chain under consideration here, and can be similarly represented. See also stages VIII - X and Section 8.

Stage VIII.

The inputs to the figure for stage VIII are the frequency distributions $\phi_{tg}(z_t)$ of incremental cadmium exposures in $\mu g/day$ from grain crop $t = 1, \dots, k$ as ingested directly as foodstuffs. The output is supposed

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

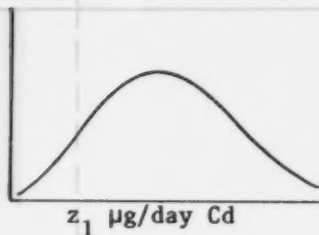
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

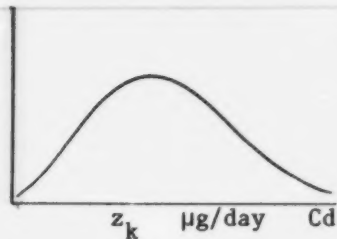
DROPPED
HEAD
BEGIN
SECTIONS
HERE

$\phi_{1g}(z_1)$
% of
Pop

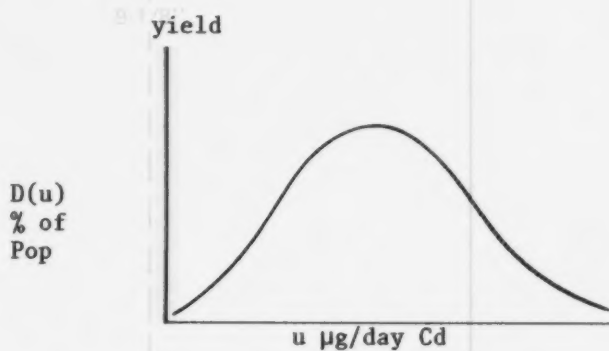


....

$\phi_{kg}(z_k)$
% of
Pop



Percents of incremental dietary daily uptakes of cadmium from crops
1, ..., k.



Percents of total incremental dietary cadmium intake u due to grain crops
1, ..., k.

Figure 15. Stage VIII.

BEGIN
LAST LINE
OF TEXT

3/8"

41

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

to be the distribution $D(u)$ of population into levels $\mu\text{g/day}$ of total dietary cadmium intake due to grain crop t . This diagram also only holds under an independence assumption. If $\phi(z_1, \dots, z_k)$ is the joint distribution of population getting dietary ingestion increments $c_1 \mu\text{g/day}$ for grain crop 1, ..., $c_k \mu\text{g/day}$ for grain crop k , then $D(u) = \int \dots \int z_1 + \dots + z_k = u \phi(z_1, \dots, z_k) dz_1 \dots dz_k$.

Let us generate a hypothetical example: suppose $k = 2$, there are two crops, and the ingestion levels from crops 1, 2 are independent. Then the marginals are

$$\phi_{1g}(z_1) = \int \phi(z_1, z_2) dz_2, \phi_{2g}(z_2) = \int \phi(z_1, z_2) dz_1 \text{ and}$$

$$D(u) = \int \phi_{1g}(z_1) \phi_{2g}(u - z_1) dz_1, \text{ the convolution of } \phi_{1g} \text{ and } \phi_{2g}.$$

In case k is arbitrary, $D(u)$ is the convolution of all the ϕ_{tg} .

Stage IX.

Stage IX represents the transfer of incremental daily dietary uptake in $u \mu\text{g/day}$ into incremental daily cadmium body load measured as $r \text{ ppmCd/day}$. The inputs to stage IX are two in number. One is the output from stage VIII, the distribution $D(u)$ of population with daily intake $u \mu\text{g/day}$. The other is the distribution $A(e)$ of population into uptake efficiencies e . The latter distribution has to be the result of experiment or extrapolation from the animal studies (see Section 8). The output of stage IX is the distribution of population at each uptake rate $r \text{ ppmCd per day}$. The simplest useful model is $r = keu$, k a constant, but there is no difficulty whatever in introducing a more complex relation at this point if found by experiment (here k converts $\mu\text{g/day}$ into ppm/day). Let $H_1(e, u)$ be the bivariate distribution of population into efficiency levels e and daily incremental diet cadmium u . This distribution is a measurable physical distribution, but in practice would be extremely difficult to sample, although the corresponding animal experiments are possible. In terms of the governing underlying distribution $H_1(e, u)$, one gets

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

$D(u)$
% of Pop

$u \text{ } \mu\text{g/day Cd}$

Percents of incremental daily cadmium at intake
rate u due to grain crops 1,...,k

and

$A(e)$
% of Pop
9-1/8"

e

Percent of population at uptake efficiency e

yield

$H(r)$
% of Pop

$r \text{ ppm Cd/day (Human)}$

Percent of population at level uptake rate.

Figure 16. Stage IX.

BEGIN
LAST LINE
OF TEXT

3/8"

43

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

$$H(r) = \int H_1(e, r/ke) de = \int H_1(r/ku, e) du$$

as the output. Here the marginal $\int H_1(e, r) dr$ is the distribution of population by efficiency level e , that is $A(e)$. In the case uptake efficiency is independent of incremental dietary cadmium level, the same calculation as for stage I gives $H(r) = \int D(u)A(e)de = \int D(r/ke)A(e)de$, the computation of the output for stage IX from the two inputs.

Stage X.

The input for stage X is the distribution $H(r)$ of population into cadmium uptake daily uptake levels r ppm/Cd per day. The simplest model of concentration is organ concentration = constant γ_t times body concentration, although calculation is equally easy for more complicated dependencies. This gives $H_t(r) = (1/\gamma_t)H_t(\gamma_t r)$ as for stage V. The determination of the final correct relationship is a matter for physiological experiment.

Stage XI.

One input for stage XI is the distribution $H_t(r)$ of incremental daily cadmium uptake for organ t into concentrations r ppm Cd/day. The other is a physiological or epidemiological response curve $i(r)$ giving in appropriate units the response i for daily incremental dose r ppm Cd. (This is the least documented area of all, and many will prefer to use only the results of stage X for population exposure distribution for organ t , regarding the dose-response information as unreliable due to short term high dose experiments and long term low dose extrapolations; but for diet cadmium this work is hardly underway.) The output is $R_t(i)$, the distribution of population into response levels i from organ incremental cadmium load, thus one gets $R_t(i) = H_t(r)(dr/di)$. More complex dose-response relations based on total dose over time are easily mirrored. Note that response can be in one of many different kinds of units - from excess mortality to physiological degradation estimates.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

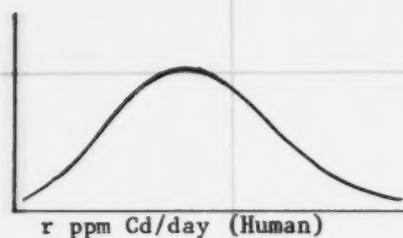
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

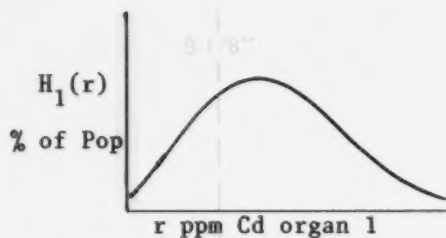
DROPPED
HEAD;
BEGIN
SECTIONS
HERE

$H(r)$
% of Pop

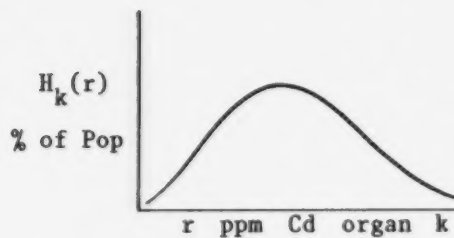


Percent of population at each uptake rate.

6-1/2"



...,



Percent of population at each uptake rate split by receiving organ.

Figure 17. Stage X.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

45

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

$H_t(r)$
% of Pop

r ppm Cd organ t

Percent of population at incremental cadmium intake r in organ t .

and

response

$i(r)$
9-1/8"

dose r ppm Cd

Dose-Response curves: dose r , response $i(r)$.

yield

$R_t(i)$
% of Pop

level i response

For organ t , distribution of population according to response level r .

Figure 18. Stage XI.

BEGIN
LAST LINE
OF TEXT

3/8"

46

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Stage XII.

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

Stages I-XI have been carried through above only for grain raised from cadmium bearing sludge and fed directly to people. The above methods, however, will adequately represent a similar chain in which grain is fed to animals and the animals are fed to man.

Next, similar calculations must be made for all alternate sludge land application disposal plans as various control points are used to exercise control. The alternative of pyrolysis can be similarly treated, for air cadmium resulting and its health effects (see Section 7). A comparison of land application and pyrolysis would require that this calculation be carried out in full in the case of pyrolysis.

Finally, similar calculations have to be made for background diet levels without sludge land application and background air levels without sludge pyrolysis. Only after all these can the relative effect of each alternative be fairly evaluated for relative importance. It appears to the authors clear that the same type of distribution modelling may be used for the other principal pathways of population exposure, respiratory or dietary, and summed for total exposures to compute background levels. It also may be seen that the corresponding series of stages for pyrolysis is very short: sludge ppm to air nanograms/cubic meter (to be obtained by experiment) plus the transfer characteristics explored in Section VII in an exploratory way plus in vivo studies of respiration of air cadmium. Figures for these stages in respiratory ingestion of air cadmium through the alternative of pyrolysis are omitted.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

Calculation of incremental population
response distribution for alternate
land application schemes using variants
of Stage I - XI

and

Calculation of incremental population
response for alternate sludge disposal schemes
(pyrolysis with air cadmium, ocean dumping
with sea food dietary cadmium)

6-1/2"

and

5-1/2"
Calculation of population response to diet
cadmium, air cadmium not due to sludge

yield

Decision maker's information base for questions such as:

Does sludge appreciably alter human diet cadmium response?

Is this response more or less severe than that due to pyrolysis?

Figure 19. Stage XII.

BEGIN
LAST LINE
OF TEXT

3/8"

48

PAGE NUMBER

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 5

Sources of Sewage Sludge: Their Role in Environmental Loading of Cadmium

(This section concerns Figure 8 for stage I.)

Introduction

From the scientific point of view, the analysis of sludge as an entry point for cadmium in the environment should begin with the relationship between influent stream levels of cadmium and sludge levels. It is, therefore, encouraging to note that work has recently begun on this relationship, and that we shall soon have information about this important component of the cadmium pathway. Up to the time of this writing, however, these studies have not advanced to the point where long term measurements are available, as they are, for example, in the case of influent-effluent oxygen demand and nutrient relationships.

Some advantages of the measurement of influent levels include the detection of point sources, short-lived discharge phenomena, high cadmium density seasonal phenomena, and other events which are obscured by the averaging effect of the storage and treatment process. These measurements will aid in the detection of certain overall patterns in discharge from treatment plants. First, a summary is given of results, then some of the policy consequences are discussed in the text that follows.

It is found, as is described in detail in the section on secular trends, that the week-to-week variation in one sewage treatment plant's output is very small compared to the variation in overall level of cadmium in the output between treatment plants. This indicates quite clearly that a monitoring strategy should be based on the fact that infrequent sampling

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

of a large number of plants will give more reliable and accurate descriptive information than continuous sampling of a small number of plants.

This is shown by the following argument. Assuming that one does not have the resources to monitor each plant continuously, but that it is necessary to estimate the distribution of temporal patterns of cadmium output among plants, one is confronted with the need to establish a sampling approach. Questions then arise as to the sampling plan: i.e., number of plants sampled and frequency of sampling. While designing the sampling plan can present a complex problem, a few salient facts emerge from very general examination. A finite resource limit implies a constraint on the (possibly weighted) product of the number of treatment plants P and the frequency of sampling F . To oversimplify for the purpose of illustration, if each sampling event costs \$1, and there are \$100 to spend each year, then one might sample 100 plants once each, or 50 plants twice, up to 1 plant 100 times, annually. The choice of F and P within the constraints is optimized for a given situation by sampling from the most variable components. Again, oversimplifying, if the range of cadmium levels among 100 plants is from 0 to 200, and the variation within each plant is nil, then it makes no sense to sample one plant 100 times. Rather, it is optimal to sample all 100 plants once. If, of course, the pattern of variation is at the other extreme, say each plant produces about the same cadmium levels on the average, but the fluctuations from week to week are enormous, then it would make sense to sample fewer plants more often. If the situation is not quite so extreme, then the analysis needs to be more sophisticated to find the optimal plan, but the rationale remains clear.

Monitoring resources should be allocated accordingly, and decisions about the organization of the monitoring effort should reflect this fact. For example, a decision to sample a large number of treatment plants infrequently may make it feasible and proper to assign the task of monitoring to a single group of experts responsible to a central authority. The advantages of such a strategy would include uniformity of assay technology, better quality control, and considerably improved expectations of

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

50

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

Typing Guide Sheet

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

statistical stability of the results. One of the many problems confronting the policymaker in this field is the lack of uniformity in experimental technique and the consequent difficulty of comparing or aggregating of data. The fact that the monitoring task might be carried out as suggested by the discussion above would offer some relief for this problem.

The information presented in the next part of this section concerns the distribution of sludge output according to level of cadmium in that output: that is, what proportion of sludge being produced in the country is of low, medium, or high cadmium level, and what are the sizes of the individual sources of sludge, according to their level of cadmium. This sort of description of the cadmium content of the nation's sludge output enables the policymaker to gauge the effect of a proposed regulatory strategy on the sludge disposal practices of the communities involved, and the effect on opportunities for various disposal methods in the future. The information is organized so that the policymaker will be able to separate the overall impact of a decision to regulate in some way into: 1) the total fraction of sludge production affected by the decisions, and 2) the number of communities affected.

It is desirable that investigators make more of their actual data available, either in published reports or in archives, so that alternative analyses may be made by others. This is particularly true for investigations in areas which are new both to the general community of scientists and to the particular investigators, as it is precisely in such situations that the practice of automatic choice of statistical method is to be avoided in favor of an exploratory approach.

Sewage Treatment Plant Characteristics

The records of sampling for cadmium at several treatment plants were studied, with the intention of characterizing the magnitude and distribution of these sources of environmental cadmium loading. Of particular concern were the time behavior of the cadmium output of these plants, how the levels vary from plant to plant, and the short term versus long term variability within each plant. These questions are highly relevant to any

BEGIN
LAST LINE
OF TEXT

3/8"

51

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

proposed solution to the problem of disposal of possibly toxic sludge, insofar as they determine the operating characteristics necessary to assure the adequacy of the disposal plan and safety of the disposal method. Proposed methods of land use, especially agricultural use, are predicated upon a certain level of stability in the cadmium output of a sludge source. Such an assumption can simplify the monitoring of cadmium loading and, indeed, has been used to help determine whether the output of a particular plant can be considered acceptable for such a disposal scheme.

To assess the impact of any proposed or hypothetical cadmium regulatory standards, as well as their effective enforceability, it is necessary to have a description of the national and regional pattern of cadmium discharges among treatment plants, and within each plant, over time. Certainly, a regulator developing a standard for cadmium based on limiting the cadmium loading associated with land application, should understand the pattern of cadmium variability in sludges so that the scheme for translating the cadmium loading limits to sludge application limits can be soundly based in reality. Examples have been found in which the regulatory standard is stated in terms of an amount of sludge from a particular plant, the assumption being that the plant's cadmium concentration is sufficiently stable to validate the implicit calculation. This assumption may very well be valid, but it would be valuable to have evidence to support it. Such evidence is examined in the following subsection.

Time Series of Cadmium Concentration in Sludge for Six Treatment Plants

Figure 20 is a schematic rendition of the results of biweekly monitoring for cadmium in the sludge of six treatment plants over a period of approximately one year. Data is from reference (8); the resulting time series has been provided to the authors of this report. In the figure, the boxes extend from the lower to the upper quartiles, and are barred at the median. The horizontal scale is logarithmic, as indicated. It is clear from the figure that the variation among plants is much greater than the variation in time within a plant. In Table 1, these summary quantities are presented in detail, as are the interquartile ranges. The table illu-

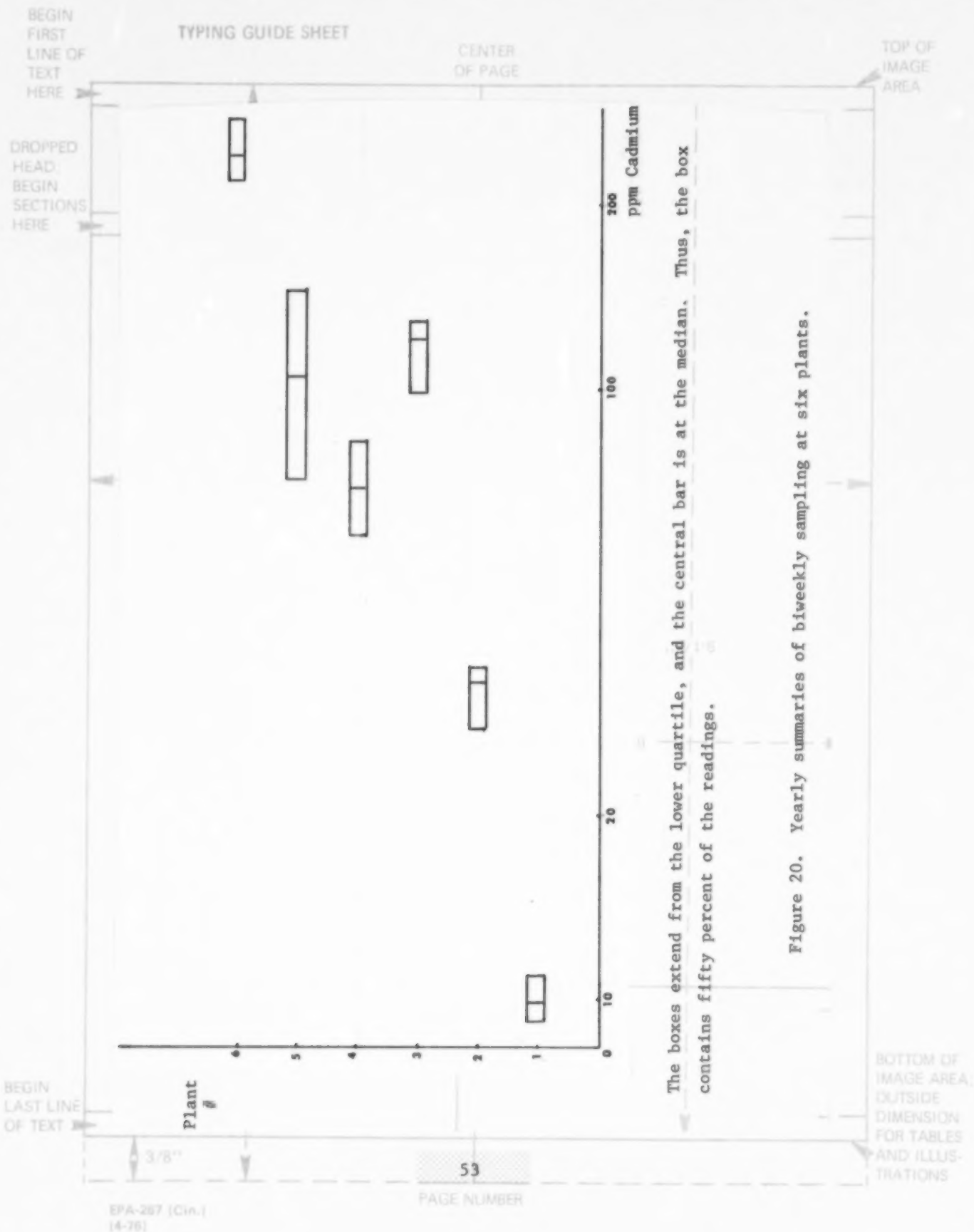


Figure 20. Yearly summaries of biweekly sampling at six plants.

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

strates the relative size of the variation within plants and among plants. As is clear, the yearly medians of cadmium readings, and the upper and lower quartiles, are very different among the six plants. When, however, the quartiles are expressed as proportions of the median, the variation is considerably less. This indicates that the differences among all readings are due mainly to the differences in level among the yearly time distributions for the plants.

The ratio of a measure of "spread," such as the interquartile range, to the measure of level, such as the median, is a measure of proportional or relative variation. The analogue in the case of standard deviation and mean is the coefficient of variation. In Table 1 the non-parametric coefficient of variation in the last column is modest for all but plant 5. This is one indication that the variation within a plant is roughly proportional to the median, or other measure of level, of the plant's output cadmium concentrations.

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

TABLE 1. SIX SEWAGE TREATMENT PLANTS
SLUDGE CADMIUM CONCENTRATIONS (ppm)*

Plant #	Yearly Median	Yearly P ₂₅	Yearly P ₇₅	P ₂₅ / Median	P ₇₅ / Median	IQR/ Median
1	10.3	8.3	11.9	.79	1.15	.36
2	34.0	28.6	35.4	.84	1.04	.20
3	125.5	101.5	134	.81	1.07	.26
4	71	59	85	.83	1.20	.37
5	108	74	156	.68	1.45	.75
6	247	229	286	.92	1.13	.21

*2 replications at approximately 2 week intervals, for one year

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

The relative stability within a plant, depicted by Figure 20, indicates the feasibility of infrequent monitoring as a reasonably accurate check on cadmium output. It is also abundantly clear that there is no uniformity among plants, and that a regulation that does not affect one might prevent another from operating at all. This qualitative variation in the magnitude of the sources of cadmium in sludge should be addressed in the regulatory process, as well as in the risk assessment.

Tables 2 and 3 measure the "smoothness" of the time series of cadmium concentrations. By taking the change from one measurement to the next one approximately two weeks later, that is, the so-called first difference, one can characterize the abruptness with which the series changes over two-week intervals. This is analogous to the first derivative in calculus, and it is easy to see that if the "first derivative" takes on a wide range of values in a time interval, then the "second derivative" must be large, and vice versa. The absolute value of the change from one measurement to another is of greatest interest, and is found in the last column of Table 2. It is interesting to note that the smallest (in terms of median cadmium concentration) plant has the smallest median absolute first difference, the next has a larger, and so on up to the largest. In other words, the smoothness of the series is inversely related to the median level. In Table 3, the summaries have been scaled to the median levels, and the results may be summarized by saying, for example, that at worst, in plant 5, at least half of the two-week differences were less than 29% of the median value, and in the smoothest case, in the sense of scaled smoothness, plant 3, we can say that half the time the cadmium concentrations changed in two weeks by less than 8% of the yearly median. The implications of this kind of statement for the monitoring and regulation process include the ability to predict the operating characteristics of the regulatory scheme for a particular plant.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

TABLE 2. SECULAR CHARACTERISTICS FOR SIX TREATMENT PLANTS*
SAMPLED AT APPROXIMATELY TWO WEEK INTERVALS

Plant #	Yearly Median (ppm Cd)	Median of First Difference	Summary of First Differences Quartiles		Absolute Difference
			lower	upper	
1	10.3	- 0.3	- 2.6	2.9	2.7
2	34.0	0.6	- 5.3	2.8	5.2
3	125.5	- 1.2	-14.1	9.6	9.6
4	71.0	1.6	- 5.0	6.7	6.7
5	108.0	- 9.1	-25.1	9.1	31.0
6	247.0	10.1	-23.6	28.6	28.6

*This table measures the differential structure of the time series of cadmium levels associated with each plant. The first column is the plant number, the second column is the median level, presented here for comparison purposes. The third column is the median of the first differences, that is, the median of $(x_{t+1} - x_t)$ where x_t is the measurement of cadmium concentration at time t . The fourth and fifth columns are, respectively, the lower and upper quartiles. The last column is the median of the absolute first differences, that is, the median $|x_{t+1} - x_t|$.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

TABLE 3. SCALED SECULAR CHARACTERISTICS*
OVER TWO WEEK INTERVALS

Plant #	Median	
	<u>Median first difference</u> Median (yearly) level	<u>absolute first difference</u> Median (yearly) level
1	-0.03	0.26
2	0.02	0.15
3	-0.001	0.08
4	0.02	0.09
5	-0.08	0.29
6	0.04	0.12

*In this table, the summaries of the previous table of first differences have been scaled to the median (yearly) level of cadmium of the plant's output. The second column of median first differences divided by median yearly level is a scaled measure of percent rate of change, and reflects the trend of the measurements. The third column, in which the median absolute value of the first differences has been scaled to the yearly overall median, is also a measure of percent change, and reflects the "abruptness" of the variation: high values implying roughness, low values implying smoothness. Compare this to Figure 15.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Composition of the Total National Sludge Output by Levels of Cadmium

DROPPED
HEAD
BEGIN
SECTIONS
HERE

In order to quantify the magnitude of the cadmium-in-sludge problem and its complexity in such a way as to make it possible to identify the highly risky sludges and estimate their contribution to the disposal task, it is necessary to categorize the total sludge output of the nation by the concentrations of cadmium. It is possible to estimate the proportions of sludge associated with a given cadmium concentration from data in reference (9). These data have been used in the analysis presented below, but this must be regarded as a tutorial example because the sample assembled by Otte accounts for about one-third of the national total, and there is no reason to suppose that the sample is not biased.

It should be noted that samples which are available are generally biased, since they often represent the "most interesting" or most extreme in some sense. It is necessary, usually, to plan carefully in order to get a useful sample, i.e., one that is not too badly biased. In addition, the summary level reported is the mean over some time interval, or some sampling replication. This is a practice which may give very great weight to unusual, but large, individual values. The entire monitoring, inventory, and sampling practice should be brought up to date in terms of its statistical methodology. Table 4 and Figures 21 through 23 are summaries of various aspects of this data base.

The total sludge output accounted for in the sample is some 3700 metric tons per day, about one third of the national total. Of this amount, about 75% is accounted for by the 13 largest cities and Boston. We have chosen to separate the largest cities into an analytic group of their own, for reasons that are summarized in the following discussion.

Although the total sludge output is important, and disposal of large, homogeneous fractions of that total is critical, the risks associated with the land application of sludge are also spread among the many smaller sources of sludge. Since the sludge application patterns on agricultural land are determined locally, and since the cadmium deposition patterns will

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
LAST LINE
OF TEXT

3/8"

59

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

result from the combination (convolution) of the sludge cadmium concentration with this pattern of use, the resulting distribution of cadmium loading has a locally determined character. For this reason, the larger single sources present in the largest cities may require special attention, and the more dispersed, smaller sources (treatment plants) may be aggregated. If the sludge from the smaller communities were not separated in the analysis, one would remain ignorant of the true pattern of cadmium concentrations because the larger sources would dominate. In essence, one would be using Chicago's sources to estimate the pattern in a small city, and the result would not reflect the true distribution of cadmium in the sludge that might be used in the city in question. This is especially true in the Otte study; only one-third of the total output of the nation has been counted in this sample, although the largest cities have been inventoried rather completely. What are missing from this sample, therefore, are sludge output data from most of the nation's smaller communities, and these data may be best estimated by studying data from the smaller communities that are included in the sample.

The risk assessment requires a characterization of cadmium concentrations that describes both the bulk of the "high volume sources" and of the multiplicity of small sources. A histogram of the percent distributions of the sludge at various cadmium concentrations from the smaller communities is in Figure 21; a table of the distribution is in Table 4. It is clear from this table that of the 25% of the total that is accounted for by the smaller cities in this sample, about two-fifths is at concentrations less than 25 ppm. A description of the sample totals, and the division into larger and smaller cities follows.

The sample accounts for about 35% of the total output of the nation. About one-fourth of this is in the smaller cities of the sample (9% of the national total). The remainder of the sample is from the 13 largest U.S. cities and Boston (26% of the national total).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

60

PAGE NUMBER

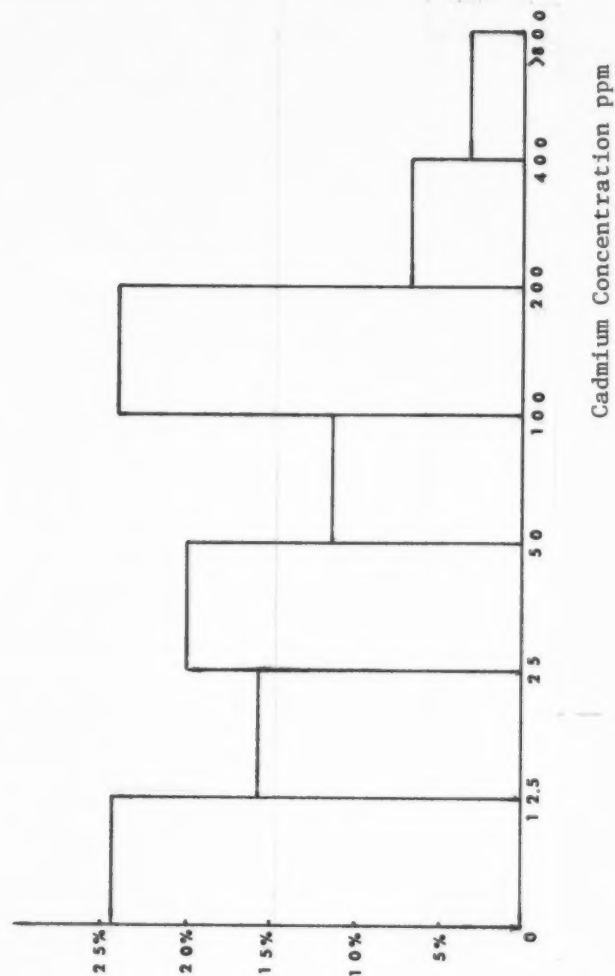
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE



The ordinate is percent of output of the smaller cities.

Figure 21. Distribution of Sludge Output by Cadmium Concentration (Excluding Thirteen Largest Cities and Boston).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

TABLE 4. JOINT DISTRIBUTION OF TREATMENT PLANTS BY SLUDGE PRODUCTION
AND CADMIUM LEVEL

Cd level (ppm)	<1.05	1.05-10.05	10.05-50.05	>50.02	Total	cum %
	1	3	--	--	4	100%
800	--	1	3	--	4	96.9%
400	--	2	2	--	4	93.8%
200	--	4	8	1	13	90.6%
100	--	3	7	--	10	90.4%
50	5	2	3	2	12	72.7%
25	12	9	7	--	28	63.2%
12.5	20	21	12	--	53	41.4%
	38	45	42	3	128	

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Figure 22 presents the distribution of sludge output by cadmium concentration for each of four large cities. These histograms make it clear that the distributions vary greatly among the four cities. In particular, almost all of Chicago's sludge output is at levels higher than almost all of New York's output. The implications of this difference to a risk analysis are considerable.

In Figure 23, a group of large cities is aggregated into a similar analysis. Unlike New York, Chicago, Boston, and Philadelphia, with the exception of Milwaukee, the cadmium concentrations of these cities' sludge outputs appears to be relatively uniform.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

63

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

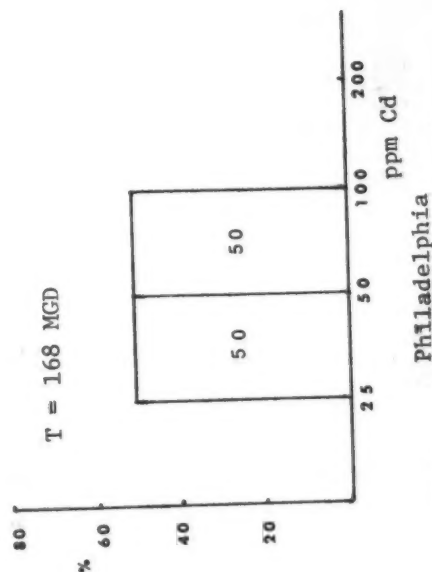
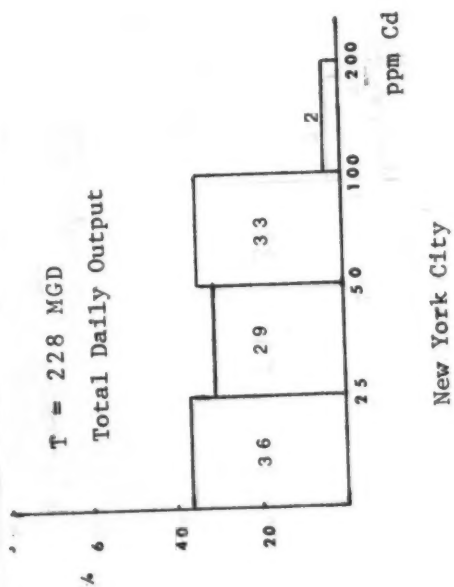
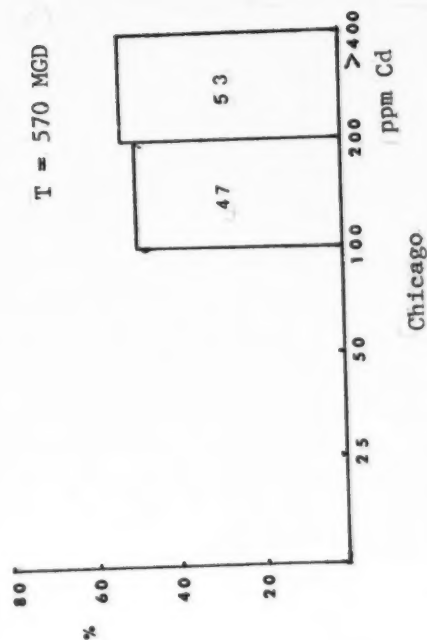
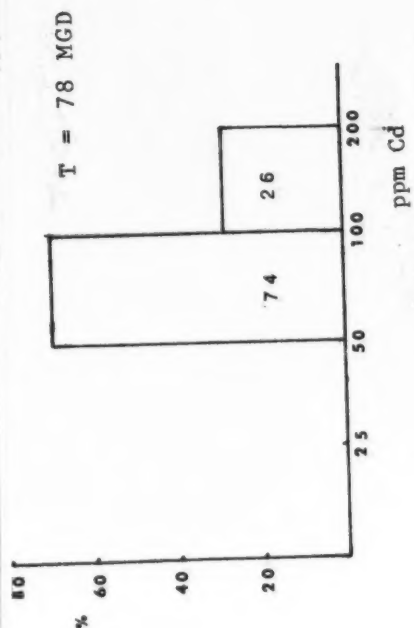


Figure 22. Percent distribution of sludge by cadmium concentration for four large cities.

BEGIN
LAST LINE
OF TEXT

3/8"

64

PAGE NUMBER

EPA-287 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

BEGIN
LAST LINE
OF TEXT

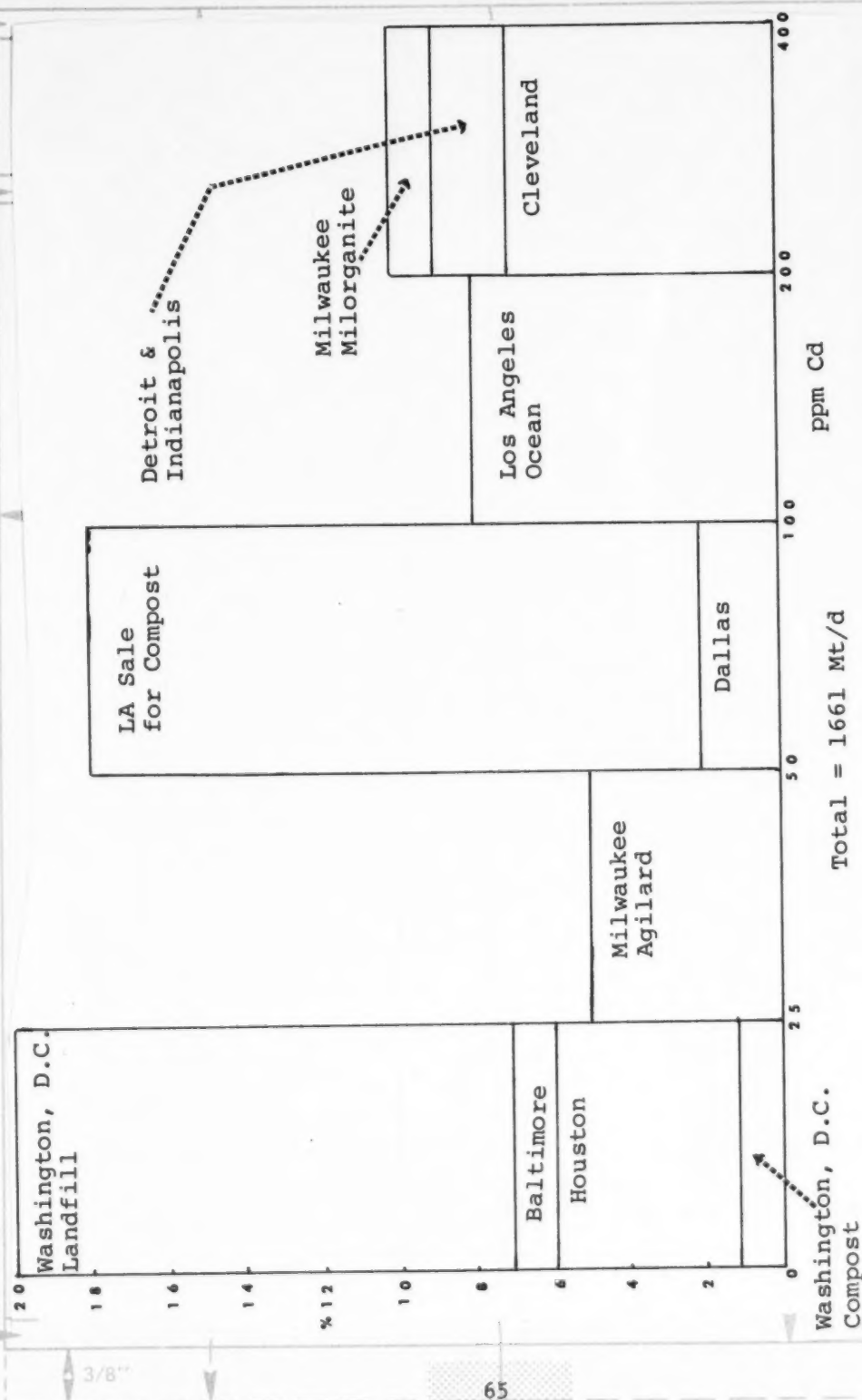


Figure 23. Percent distribution of sludge by cadmium concentration for some large cities.

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Implications for Risk Assessment

The preceding analysis and extensions thereof may be used to complete the initial phase of the risk assessment methodology as applied to the land application of sewage sludge. In terms of the objectives of the project, the preceding analysis enables the feasibility of the risk assessment methodology to be evaluated at this stage. It appears that the method is quite feasible, although a more complete inventory of sludge cadmium concentrations would be desirable in order for the assessment to be made on the most secure possible basis. The separation of the analysis into the smaller communities and the largest cities reflects the strategy of the risk assessment. In order to assess the consequences of a given pattern of national sludge application to agricultural land, it is necessary to include any substantial interaction between the regional particulars of the application regimen and the local character of the sludge. If, for example, the application program is designed to be responsive in some degree to the local sludge characteristics, then the distributions of sludge concentrations of cadmium and the application rates are not convolved as independent variables in the risk assessment to produce the distribution of loading rates. Rather, there is a joint distribution of rates of application and cadmium concentration, which governs the distribution of the product of application rates and concentrations, i.e., the loading rates.

The easiest way to approach this problem is to propose that the largest cities will have the most specifically designed application programs, and that the size of the sources in these cities will make it possible to program the use pattern efficiently in order to minimize the risk. It is less likely that the bulk of the smaller cities will be in a position to tailor the use patterns to the particular sludges, since there is likely to be a single source of sludge in a small community. Among the largest cities, the risk assessment will be sensitive to the multiplicity of "blocks" of concentration. For example, from Figure 22, it seems that Philadelphia has two rather different types of sludge in terms of cadmium concentration, and that the total output is split evenly between these two

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

BEGIN
LAST LINE
OF TEXT

3/8"

66

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

types. By contrast, from Figure 23, Cleveland seems to have more homogeneous sludge of high cadmium content.

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

Of course, if the application pattern is not at all responsive to information of this sort as to the level of cadmium in the sludge, then the risk analysis would reflect this by considering the sludge independently of its origin. In that case, the total distribution of output by cadmium concentration would be entered into the application scheme to produce the distribution of loading rates. If, as seems desirable for the larger cities, the information about the level of cadmium in the sludge from a particular plant is used to condition the decisions of sludge management, then the stratification described by the preceding discussion is appropriate.

This presentation has proceeded from the assumption that the most likely scenario will find the smaller cities less able to condition the application pattern by the details of the cadmium concentration, and that the largest cities will find it relatively easier to do so due to economies of scale. This is a control point of considerable leverage, and the feedback from the particular control mechanism applied at this point will influence the assessment of risk to a considerable degree.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 6

Application Rates as Determinants of Soil Concentration

(This section concerns Figures 9, 10, stages II, III)

Introduction

After reconstructing the distribution of cadmium concentrations in sludge as described in the previous section, one is in a position to combine this distribution with a pattern of sludge use rates. This combination may be based on regulatory norms, or, more likely, on agricultural considerations. However it is derived, it is necessary to have an estimate of the rates of application that will be used, and in what relative proportions. If, for example, 50% of the sludge will be applied at less than 20 metric tons per hectare, and 25% at 20 to 30 MT/ha, etc., this constitutes the distribution of application rates that must be estimated. In combination with the distribution of concentrations, this will yield an estimate of the distribution of cadmium loading rates: for example, the proportion of land at each level of cadmium loading, measured by kilograms of cadmium per hectare.

The next step in the cadmium pathway following land application is the response of the soil to these loading patterns. The word patterns is important, because one will be interested in the temporal sequence of loading rates, considered as a single scheme, and in the distribution of such schemes. If the temporal sequence of application were of no significance, one might consider only cross-sectional rates, however, it will be shown later in this report that the effects of application trends are in fact significant, forcing consideration of the application pattern.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

In this and the following section, the causal steps in the translocation of the applied cadmium are investigated, from application patterns to soil concentrations and from soil concentrations to plant uptake. By reanalyzing from scratch the results of various experiments in which cadmium-bearing sludge or cadmium salts have been applied to land, the authors have been able to elucidate the effect of the patterns of application on the levels of cadmium in the soil. Our conclusions may be summarized as follows.

Pooling yearly results within a study, one finds a rather close linear relationship between total soil levels of cadmium and total cumulative cadmium applied up to and including the year prior to measurement. If the year by year results are examined, there emerges a "start-up effect." This indicates that the linear relationship between cumulative cadmium and soil levels is at a somewhat higher slope in the first year of the soil measurement than it is in the succeeding years of measurement. The years following the first have a homogeneous response, and the start-up effect, i.e., the difference in slope between the first year's response and the common response of the succeeding years, is rather small compared to the slopes involved.

This result may indicate, however, that there is danger of overestimating the soil response to cadmium application by using single-year studies as a substitute for extended studies. It is recommended that attempts to estimate the response parameters in the real world employ experimental designs which are as close as possible to the physically realizable conditions in proposed and actual practice. By this we mean that an experiment intended to estimate the effects of a sludge application scheme that will continue over several years should itself have a design which extends in time. A single-year study cannot be expected to produce any information on the effect of multi-year application of sludge, whereas a study with several consecutive years of controlled application and concurrent measurement of uptake or soil content will have the capability to estimate the behavior of the natural system. Such studies, which have a

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

69

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

temporal axis, are referred to by experiment designers as "longitudinal studies," in order to distinguish them from the "cross-sectional" studies which involve only one temporal measurement point.

The most useful longitudinal study, carried out by Hinesly et al. (reference 10 p. 305) has a complicating feature. The sludge application rates were drastically reduced in mid-experiment, which introduces a time series effect in the input variable. This makes analysis very difficult, as the yearly application rates cannot be used as orthogonal or independent variables in a regression or analysis of variance.

The actual effects of annual or cumulative application are confounded severely with the time sequence effects, and it is difficult to separate them. In future work along these lines it would be well for researchers to consider the advantages (to the analysis) of an experimental design which has more balance and less trend. The drawbacks of the single-year studies are also considerable; they resemble the difficulties with high dose animal studies in toxicology, in which high doses and selection for susceptibility of the experimental species are then extrapolated down to the actual levels of interest.

Considerations of time and expense aside, it is clear that the use of artificial designs such as single-year studies or the use of cadmium salts as surrogates for sludge, should be avoided in cases in which there is no generally agreed upon means of translation to actual practice. In particular, analysis shows that in single-year studies, where investigators have been faced with the need to produce response in plants or animals in such a short time, they have had to use simulations with cadmium salts instead of the actual product of sludge treatment plants. These studies have not squarely faced the difficulties of generalizing such results to the situation of land application of sludge, and we have found that the resulting picture is quite distorted. In fact, the present authors know of no study in which the investigators have demonstrated, or described, a mathematical or statistical relationship between the results of applying

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

salts of cadmium in a greenhouse and the results of applying sludge in the field. In the absence of such a hypothetical or actual relationship, it is impossible to have much confidence in the extrapolation or transfer of results from salt studies to the situation encountered in the actual process of sludge application to agricultural land.

In principle, there is nothing wrong with a study designed to ascertain whether there is an association between the results of using salts and the results of using sludge, thus validating the practice of using salts as a surrogate for sludge. Without such experiments, however, the quantitative relationship between the reported results of a salt experiment and the (unobserved) hypothetical results of a sludge experiment is unknown, nor is it known whether there is any useful correlation at all between artificial salt results and real sludge results. In short, there is no way to translate the data describing response to salt into data describing response to sludge without an experimentally derived empirical rule of known precision.

As the first step in the chain of events linking land application of cadmium-bearing sludge to human exposure following ingestion of plants which have taken up cadmium, we have examined the effects on soil levels of the various patterns of land application. There are several reports in the literature which describe measurement of soil levels of cadmium subsequent to application of sludge or cadmium salts to land. Although these reports are of widely differing experimental plans, they all indicate a rather close, simple, and monotonic relationship in which soil cadmium levels rise in response to application. Details of these experiments follow.

Study No. 1 (Jones, Hinesly, Ziegler, reference 11)

The purpose of this Greenhouse soybean study was to estimate the effects of the joint application of sludge and cadmium acetate on soil cadmium levels and plant uptake and to discover any interaction effect when both cadmium sources are present. The cadmium-bearing sludge and cadmium acetates were mixed in sixteen different combinations. The four levels corresponded to the administration of 0, 21.8, 43.6, and 87.1 metric tons of sludge per hectare, in terms of the amounts of cadmium applied. This is

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

known as a 4^2 factorial design, and the authors proceeded with a standard analysis of variance of the 0.1 Normal (N) HCl extractable cadmium in the soil.

The present authors adopted a somewhat different approach. They fit this data with a model that is additive in the cadmium applied in the two forms. The results indicate that the soil levels are indeed an additive linear function of the application rates, with no apparent interaction. It is interesting to note, as shown in Table 5, that the response to cadmium acetate application rate appears to be less vigorous than the response to cadmium in sludge. This must be interpreted very carefully, because of an acknowledged experimental difficulty that developed, which is explained below.

6-1/2"

TABLE 5. MAIN EFFECTS: CADMIUM PPM IN SOIL*

9-1/8"

Application rate	0	Low	Medium	High
Sludge Cadmium	-6.9	-1.1	4.0	14.0
Cadmium Acetate	-3.0	-1.0	0.3	4.0

*The numbers indicate the increase or decrease over a base (median) level of soil cadmium due to each experimental condition. Thus, cadmium acetate "Low" and sludge "Medium" yields $-1.0 + 4.0 = 3.0$ ppm soil cadmium over the base level.

In the analysis of variance, the relatively smaller main effects for the cadmium salt are perhaps attributable to the fact that, in order to

BEGIN
LAST LINE
OF TEXT

3/8"

72

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

avoid toxicity, the plots were leached with water to a constant conductivity equal to that of untreated soil. The differential solubility of the cadmium salt and the sludge-borne cadmium may have increased the proportion of cadmium salt lost in the leaching process. The effects have been calculated assuming an additive model. The fit is rather good, with one "outlier," or extreme value, in the residuals.

Study No. 2 (Hinesly and Hansen reference 10, p. 305)

In order to test the effects of land application of cadmium-bearing sludge on uptake in soybeans, Hinesly and Hansen, applied sludge at four rates: a conventional largest rate called the maximum, $\frac{1}{2}$ -maximum, $\frac{1}{4}$ -maximum, and 0, annually for a period of eight years. The maximum rate varied widely from year to year in response to toxicity, soil nitrogen and the effects of weather on soil drainage. Each year, on each plot, the soil level of cadmium was measured, at depths of 0-15 cm and 15-30 cm. Since the total amount of cadmium applied to the soil as of a given measurement is presumably the total applied cadmium up to and including the prior year, we have graphed the soil measurements for the 0-15 depth against the total applied cadmium through the prior year. In the accompanying Figure 24, it can be seen that the soil levels are determined rather closely as a function of cumulative applied cadmium.

In explaining the terms in the graph, it should be remarked that the sludge applications were terminated after the first four years in half of the plots because of phosphorous toxicity, and from that point on those plots received no sludge. They are referred to as the "terminated" plots. The other plots, referred to as the "continued" plots, received sludge at the indicated rates for the remaining four years. There does not seem to be any difference in the responses of the two groups, as can be seen in the graph. Because a straight line of slope one fits the scatter plot on the full logarithmic scale, it can be seen that the soil level is a linear multiple of the cumulative applied cadmium. As a general estimate, the cadmium level in soil (in ppm) is approximately 0.4 times the applied cadmium in kilograms-per-hectare. This figure serves as a benchmark for comparison to other studies' results.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

ppm
Cd
Soil

10

1

3

10

100

kg/ha

- * = Continued Plots
- = Terminated Plots

Figure 24. Cadmium concentrations in the 0-15 CM stratum by cumulative applied cadmium (through prior year).
(Both scales are logarithmic, base ten).

BEGIN
LAST LINE
OF TEXT

3/8"

74

PAGE NUMBER

EPA-287 (Cir.)
(4-76)

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Study No. 3 (Hinesly and Hansen, reference 10, p. 10)

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

In a related series of experiments, Hinesly and Hansen prepared three different types of soil and duplicated them in a North and South series. From 1969 to 1976, sludge was applied at rates of maximum, $\frac{1}{2}$ -maximum, $\frac{1}{4}$ -maximum, and 0, the maximum rate varying from year to year. The measurements for soil cadmium in the 0-15 cm depth range are plotted in accompanying Figures 25 and 26 against the cumulative applied cadmium, as in study 2, above. Again it can be seen that the soil cadmium levels are a multiple of the cumulative applied cadmium; an estimate of about 0.3 for the constant multiple will serve quite well. It is important to note that the "constant multiple" is a change of scale from kg/hectare of applied cadmium to ppm soil cadmium. It does not refer to the fraction of applied cadmium that shows up in the soil. That fraction cannot be determined without much more detailed information about soil levels. It is of some interest that the levels for the 1971 year in the North series, and less strikingly, the South series, are at a higher multiple of the cumulative cadmium. In addition, there is some variation in the soil response, with the Plainfield soil apparently responding with a somewhat larger constant factor. In fact, a resistant analysis of variance shows that there is a "start-up effect" in the 1971 soil levels; they are elevated in the first year of testing, and fall in the second year, after which they rise again in response to the cumulative cadmium. It may be that the dip in the second year of measurement occurs in response to cadmium loss due to sampling error or undetected leaching, etc. It would be of some interest to have this matter explained, as it may be related to the larger problem of translocation in the subsoil, and leaching by drainage and runoff.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

75

PAGE NUMBER

TYPING GUIDE SHEET

BEGIN
FIRST
LINE OF
TEXT
HERE

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

ppm
Cd
Soil

10

1

10

100

kg/ha Applied Cadmium

* = 1971

• = Other Years

Figure 25. Soil cadmium concentrations, 0-15 CM depth, by
cumulative applied cadmium (through prior year).
(Both scales are logarithmic, base ten.)
North Series

BEGIN
LAST LINE
OF TEXT

3/8"

76

PAGE NUMBER

EPA-287 (Cir.)
(4-76)

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

ppm
Cd
Soil

10

1

10

100

kg/ha Applied Cadmium

* = 1971

• = Other Years

Figure 26. Soil cadmium concentrations, 0-15 CM depth, by
cumulative applied cadmium, (through prior year).
(Both scales are logarithmic, base ten)
South Series

BEGIN
LAST LINE
OF TEXT

3/8"

77

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Study No. 4 (Hinesley and Hansen, reference 10, p. 250)

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

In an experiment designed to study uptake in corn, Hinesley and Hansen applied sludge at the usual four rates for ten years to Blount soil. A plot of this group of measurements that corresponds to the previous analyses is presented in Figure 27. The estimate of the constant of proportionality is between .2 and .25, which is lower than the estimates given previously, but by a relatively small amount compared to the uncertainty. In this untransformed plot, one can see quite clearly the linearity of the response of soil levels to cumulative applied cadmium.

The purpose of these reanalyses and summaries of the soil response to cadmium application was to establish the interexperiment variability and reliability of various estimations of the functional relationship characterizing this response. It has been found that the experiments agree on the approximate linearity of the response, although the estimates of the coefficient of response differ somewhat. In addition, the previously mentioned "start-up" effect, in which the first year of a multi-year application program produces a higher soil response than the subsequent years, has been observed. Note that this does not mean that the actual level of cadmium in the soil goes down, but rather that the response of the soil to cumulative applied cadmium is greater in the first year than in subsequent years.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

78

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

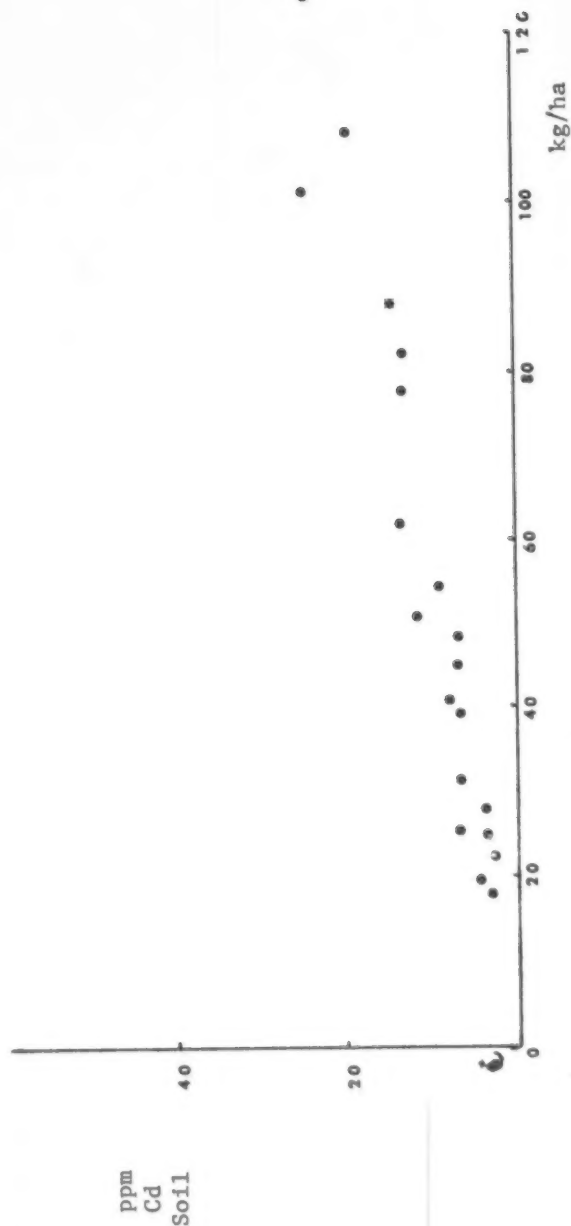


Figure 27. Soil cadmium concentrations, 0-15 CM depth, by cumulative applied cadmium (untransformed scales).

BEGIN
LAST LINE
OF TEXT

3/8"

79

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 7

Uptake in Plants in Response to Soil Cadmium Levels

(This concerns Figures 11, 12, stages IV, V)

Introduction

Because of the special purposes of this investigation, it has been necessary to subject the raw data, as they were available in the studies we have cited, to a complete reanalysis using an appropriate exploratory approach. By so doing, it has been discovered that certain studies are considerably more valuable to our purposes than others. Single-year studies have tended to overestimate vastly the expected uptake response rate of plants to soil cadmium levels, and, therefore, to cumulative applications. Longitudinal multi-year studies reveal a pattern of uptake rising in response to soil levels, with increasing variation at the higher levels of soil cadmium, but with an overall response rate that is much lower than the single-year studies indicate. In fact, one can conclude that soil level is an unreliable predictor of uptake in plants, due to the extreme variation in response.

One can, however, account for much of this variation by examining the data using time as a covariate, and we have found a definite trend in response rates between soil and plant. It appears that the response rate is quite high, for example, at the beginning of the study, when the cadmium has been recently applied. The response rate drops substantially as the cadmium burden of the soil ages. This suggests interesting hypotheses for future testing, and casts serious doubt on the relevance of single-year studies to the risk assessment process. It also must be re-emphasized that these results appear only after a close exploration of the raw data, and are obscured by the current practice of entering the results of measure-

BEGIN
LAST LINE
OF TEXT

3/8"

80

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

ments into a routine mechanical statistical analysis before, or instead of, attempting to deal with the undigested, unpooled data.

The authors would have liked very much to have seen more of the raw data, in particular, the means of replications, and less of the summary statistics. It is nearly impossible to estimate the disperison of the distributions involved whenever all results reported are the result of some routine summarizing procedure. Further, we would have found the data much more useful had equal attention been paid to explanatory variables such as time and pattern of application. The outcome variables have been consistently measured with more care and reported more exhaustively, with more complete documentation, than the equally important input variables. This lack of even-handedness extends to the design, in which, for example, the input variables have turned out to be highly correlated as a consequence of the breakdown of the experimental plan. Typical of such breakdown has been the development of severe toxic response due to the extraordinary doses of sludge applied, necessitating the reduction to nearly zero of the application rates in the next years. This year-to-year variation in the application rates is extremely unfortunate because it introduces confounding sources of variation. It is clear that if application rates over several years prior to growth influence plant uptake response, violent year-to-year fluctuations in application rates make these influences difficult to isolate.

Having demonstrated that the levels of cadmium in the soil are responsive to cumulative application rates after an initially high "start-up" level, it is necessary to try to relate these levels to plant uptake. This approach establishes the level of reliability, as reflected by the inter-experiment agreement, of basic measures such as uptake rates, and their value as estimators of the fundamental properties of the systems involved in the exposure of humans to sludge-borne cadmium. This task is severely complicated by the fact that uptake varies widely among species (Bingham, et. al., reference 12), among cultivars in a species (Hinesly, reference 13), and among the parts of a plant (Hinesly and Hansen, reference 10). Much of the research into this relationship has been conducted cross-

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

sectionally: that is, by adding sludge to land and growing one harvest of plants which are assayed for cadmium. These studies have a severe deficiency which limits the generalizability of their conclusions.

This deficiency is related to the finding, from studies which are extended over several years, that the uptake in plants is not directly responsive to soil levels or to total accumulated applied cadmium. As previously discussed, these results indicate that estimates based on single-year experiments cannot be applied freely to predict the effects of continuous, extended application of sludge.

In what follows, the relevant literature is reviewed, with additional analyses where feasible. We distinguish three types of study: 1) pure single-year, 2) single-year after several years of application, and 3) longitudinal studies in which uptake and application are recorded for several consecutive years.

Pure Single-Year Studies

Study No. 1. (Pettersson, reference 14.) The principle findings of this study are that the variation in uptake among species, and within a species, between cultivars, is of the same or greater magnitude than the uptake variation due to differences in soil cadmium levels.

Study No. 2. (Bingham, et. al., reference 12). The authors of this study simulated cadmium bearing sludge by adding varying amounts of CdSO_4 to low cadmium residential sludge, and then grew various species of agricultural plants on these soils. The accompanying graphs illustrate the relationship between uptake and soil levels, for leaf and grain of soybean, wheat, and corn. The study includes additional data for other plants, but for purposes of comparison with the longitudinal studies it will suffice to consider these three.

Figure 28 indicates that the leaf uptake levels for all three species increased at higher soil levels. In fact, it appears that doubling the soil cadmium adds about 7 ppm to the soy and wheat leaf, and

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Cd
ppm
Leaf

60

50

40

30

20

10

● = Soybean Leaf

■ = Corn

▲ = Wheat

1

10

100

(Logarithmic Scale)

ppm Cd Soil

BEGIN
LAST LINE
OF TEXT

Figure 28. Uptake in leaf for three crops, by soil cadmium levels.

3/8"

83

PAGE NUMBER

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

about 13 ppm to the corn leaf. These values are median increases for the uptake levels at the doubling of soil levels. Figure 29 indicates that the grain response is more complicated, a finding that is repeated elsewhere in the literature. Soybean in particular, has a rather complicated response, probably due in part to toxicity. Indeed, of the three, soybean yields were adversely affected at the lowest levels of cadmium, as may be seen by the fact that the soil cadmium levels at which there was a 25% reduction in yield were: soybean, 5 ppm; corn, 18 ppm; wheat, 50 ppm. In any case, we again take as estimates the median additional ppm uptake due to a doubling of the soil cadmium. These are: soybean, +6; corn, +1; wheat, +3. These numbers will enable us to compare the results of this study with others to see whether enriching sludge with cadmium salts is an appropriate investigative method, or a misleading simulation of the results of long-term sludge application.

9 1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

84

PAGE NUMBER

TYPING GUIDE SHEET

BEGIN
FIRST
LINE OF
TEXT
HERE

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

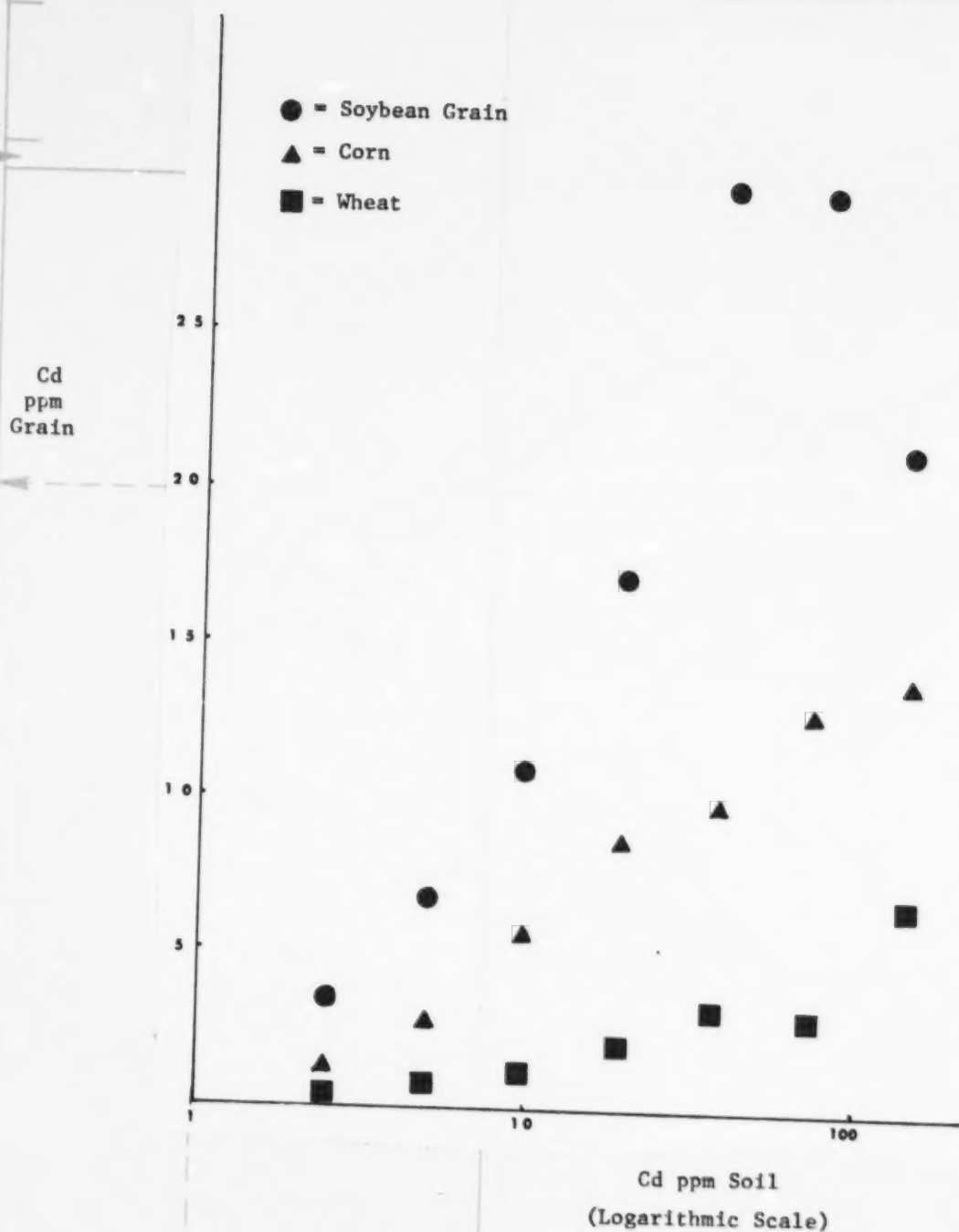


Figure 29. Uptake in grain for three crops, by soil cadmium levels.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

Study No. 3. (Jones, Hinesly, Ziegler, reference 11.) In this factorial study of the relative effects of cadmium-bearing sludge and sludge simulated with cadmium acetate salts, [described in the section on soil levels] the authors recorded levels in soybean leaf and soil, under the 4^2 factors of 0, 2, 4, and 8 levels of sludge and salt. The plot of leaf levels by soil levels that follows is derived from these data. The authors also report a response surface for seed levels for the various conditions, but due to the highly non-resistant methods employed, we are not able to evaluate the validity of the results. It would seem, from the accompanying Figure 30, that at least a fourfold increase in soil cadmium levels (using cadmium acetate) is required to produce an increase of 5 ppm in the leaf levels. This is somewhat different from the results of the Bingham, et al. investigation, in which a doubling of soil levels using cadmium sulfate produced an increase of about 7 ppm in soybean leaf. Notwithstanding this difference, which may be due to acetate versus sulfate, the form of the relationship is the same in both investigations: leaf level is a linear function of the logarithm of soil level. Multiplicative changes in the soil level produce additive changes in the leaf levels. These relationships need to be interpreted with the caveat that they are derived from single-year studies, and may not hold for the extended situation, for extreme cadmium loading conditions, or for other forms of cadmium.

In Figure 30, the reader will notice two "outliers", or extreme values, which correspond to the sludge application levels 4 and 8, at salt level 0. We have no adequate explanation of these values. They are troublesome, for if we attach any weight to them, they would seem to indicate a dramatic response to increases in soil cadmium levels. Indeed, the analysis performed by the original authors, ANOVA, relies on these leaf readings rather heavily for the estimation of the sludge effect. The fact that the data are the result of only three replications and that the ANOVA procedure relies so heavily on the mean as a measure of location, suggests that the possible presence of a small number of outliers might be severely skewing the analysis. Based on the "out of control" quality of the data that is available to us, we doubt that the analysis of variance in its

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

parametric form is the proper tool for assessing main and interaction effects. It would have been useful to have seen the raw data of the replications, rather than the summaries.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

87

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

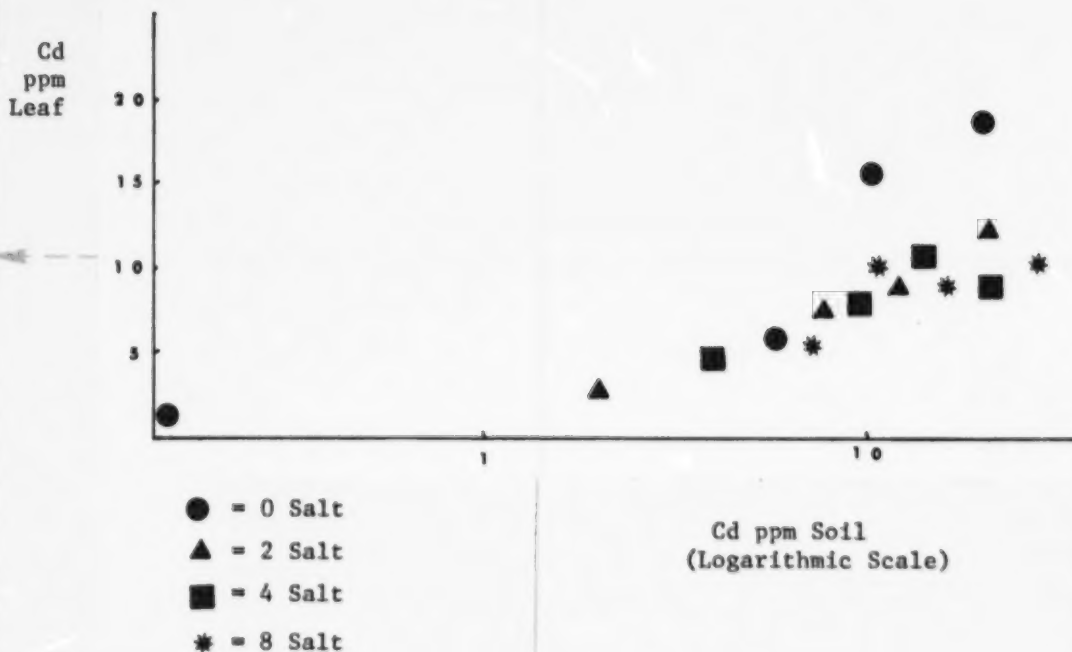


Figure 30. Soybean leaf levels by soil levels,
split by salt application rates.

BEGIN
LAST LINE
OF TEXT

3/8"

EPA-287 (Cir.)
(4-76)

88

PAGE NUMBER

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Single Harvest Studies After Several Years of Accumulation

Study No. 4 (Hinesly, et al., reference 13). After seven years of sludge application at several different rates, plots of Blount soil were planted with twenty different corn inbreds. The leaf and grain cadmium levels were measured at harvest, and the soil levels were measured at the four different rates of sludge application. In the accompanying graph, Figure 31, leaf levels are plotted against soil level. This figure allows one to compare the results of the Bingham single-year CdSO_4 experiment, reported earlier. The reference line in the accompanying graph is the approximate relationship between soil levels and leaf levels reported in the Bingham study. It is immediately apparent that the response to accumulated cadmium is much different from the response to annually applied cadmium. In particular, the form of the relationship is radically altered, and in Figure 31, it can be seen that the relationship has actually reversed concavity. It is now concave upward in the longitudinal study. The Bingham results, in contrast, would indicate a downward concavity, since the leaf level was linear in relation to the log of the soil level. Probably even more striking is the level of the relationship between the Hinesly study and the Bingham study. This contrast is demonstrated by the line labeled "Bingham reference line" in Figure 31. Because the Bingham study is a greenhouse study in field soil and the Hinesly study is a field study, there is a ready explanation for the wide difference in results. It appears to be accepted from general experience that cadmium uptake is more avid in greenhouse than in field. Also the Bingham study used a hybrid seed of sweet corn, and Hinesly used an inbred line of field corn. This again indicates the inadequacy of the experimental design in the Bingham study for resolving questions of relevance to the long-term use of cadmium-bearing sludge on agricultural land. This is not a criticism of the Bingham methodology; rather, it is a caveat about its application to the particular case in hand. No doubt the Bingham study allows many conclusions about the uptake of cadmium in plants under certain circumstances, and is valuable for that reason. It represents a class of research designs, however, that should not be used to decide questions about the longitudinal use of sludge as a soil application.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

89

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

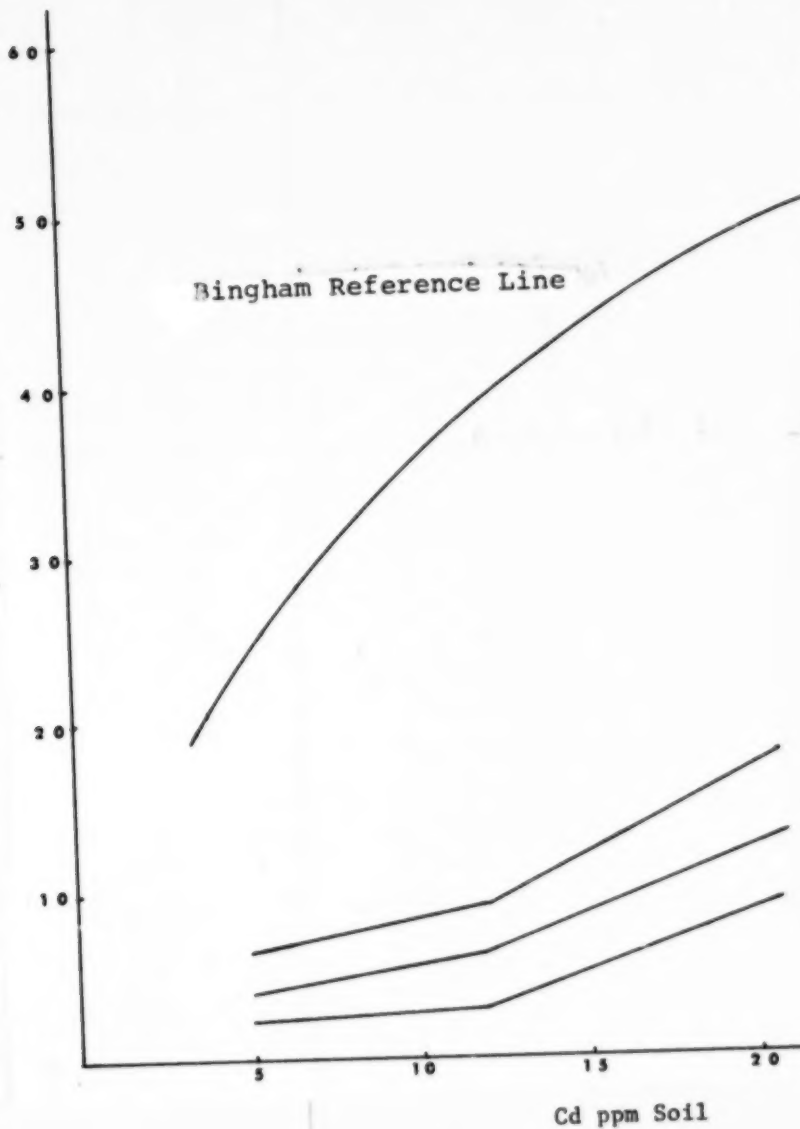
TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Cd
ppm
Leaf

Bingham Reference Line

9-1/8"



M = Median
Q = Quartile

BEGIN
LAST LINE
OF TEXT

Figure 31. Leaf cadmium levels by soil cadmium concentrations.

3/8"

90

PAGE NUMBER

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

The same results may be seen from an analysis of the grain uptake as a function of soil levels in this study, as compared with the Bingham results. Figure 32 presents these data, and the same general remarks made about the shape and level differences of Figure 31 apply here. It should be noted that the representations in Figures 31 and 32 are of the central order statistics, that is, the median and upper and lower quartiles. This may be thought of as the "confidence band" for the study.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

91

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

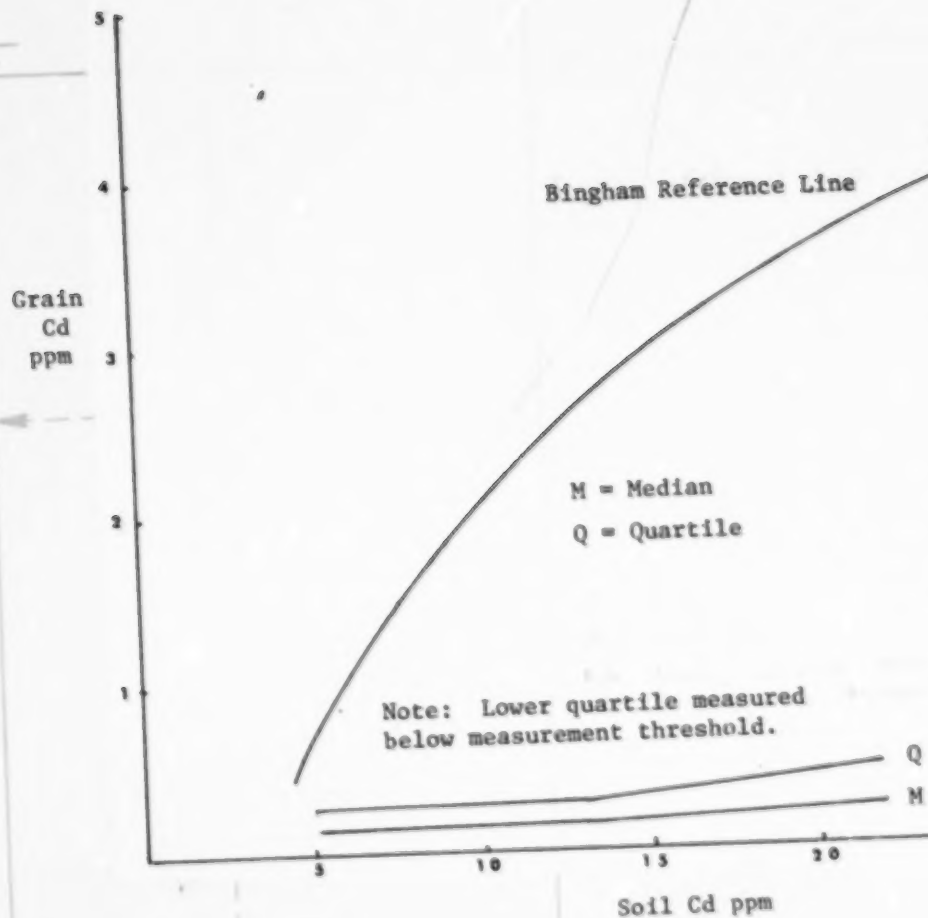


Figure 32. Grain cadmium concentrations by soil concentrations.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Study No. 5. (Chaney, Hornick, Simon, reference 15.) In 1974, 1975, and 1976, Chaney and co-workers planted various crops on land which had had sludge applied for many years. The plots were from several different regions of the east, and the cadmium content of the sludges varied greatly. Because of variation in other soil qualities and the lack of raw data in the article, it is not possible to relate uptake to soil levels in a simple way. For example, soil cadmium totals in the range of 3-10 ppm produced corn grain levels of .21 to .85 ppm with a weak positive association, as exhibited in Figure 33. These levels are somewhat lower than the corresponding results reported in the Bingham study. Further, it can be seen from the data provided for city 13 (see Chaney) that the variation between locations is so large that it obscures any relationship with soil levels. Oat grain levels, for example, seem to be negatively associated with soil levels if results from different plots are pooled; there are similar variations in red clover uptake.

9-1/8"
In Figure 33, the underlined points represent recent applications of sludge cake, and Chaney interprets the magnitude of the uptake as a function of recent cadmium rather than accumulated cadmium. The pH of the soils is implicated as a determinant of both availability and uptake. In sum, it appears that this study provides some evidence for the thesis that the uptake in plants depends on more factors than just soil levels, whether the levels are total or extractable, and that the recency of the cadmium loading and the pH of the soil are among the influential factors.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

93

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

Note: Underlined points
represent recent application
of sludge cake.

Corn
Grain
Cd
ppm

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

5-1/2"

9-1/8"

Soil Cd ppm

0 2 4 6 8 10

Figure 33. Corn grain cadmium by soil cadmium.

3/8"

94

PAGE NUMBER

EPA-287 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
LAST LINE
OF TEXT

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Longitudinal Studies

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Study No. 6. (Hinesly and Hansen reference 10, p. 10.) In this study, which has been described in a prior section, the measurement of soil levels and leaf and grain uptake for the four years 1971-1974, provides a way to assess the changing pattern of dependence of uptake on soil levels. To provide an idea of the relative levels of leaf and grain, Figure 34 is a compressed plot of uptakes against soil levels. It can be seen that grain levels are on the order of one-tenth the leaf levels. From this graph we can also see the recurrent pattern in which the levels of uptake rise with soil levels, as does the dispersion; the conditional distribution of uptake levels is much higher at high soil levels than at low soil levels. This finding, which is characteristic of the data encountered in this project, requires special attention in the analysis. In particular, ANOVA and regression methods which are not highly robust against heteroscedasticity should be avoided in favor of non-parametric methods in exploring dependence and other relationships.

9-1/8"

One begins to see an explanation for the scatter when we examine the points which have been coded for year of observation. In the graphs in Figure 34, we can see that the 1971 and 1972 values rise much more steeply than the 1973 and 1974 values, both for leaf and grain. By cutting the soil values at roughly quartile intervals and plotting the points (median interval soil level, median interval uptake) and the 25% points at each interval for the uptakes, we generate the plots that follow in Figures 35 and 36. The upper group is the 1971-1972 result, and the lower is the 1973-1974 result for leaf and grain. It is clear from these plots that the uptake characteristics as a function of soil levels change over time. Soils were limed in 1972, and the pH change lowered cadmium uptake in 1973 and 1974. If we interpret the graphs as not representing random events, we may conjecture that the dependency weakens in time. If there were more soil measurements we could have undertaken a much more thorough a job of analysis, but these results are suggestive.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

95

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

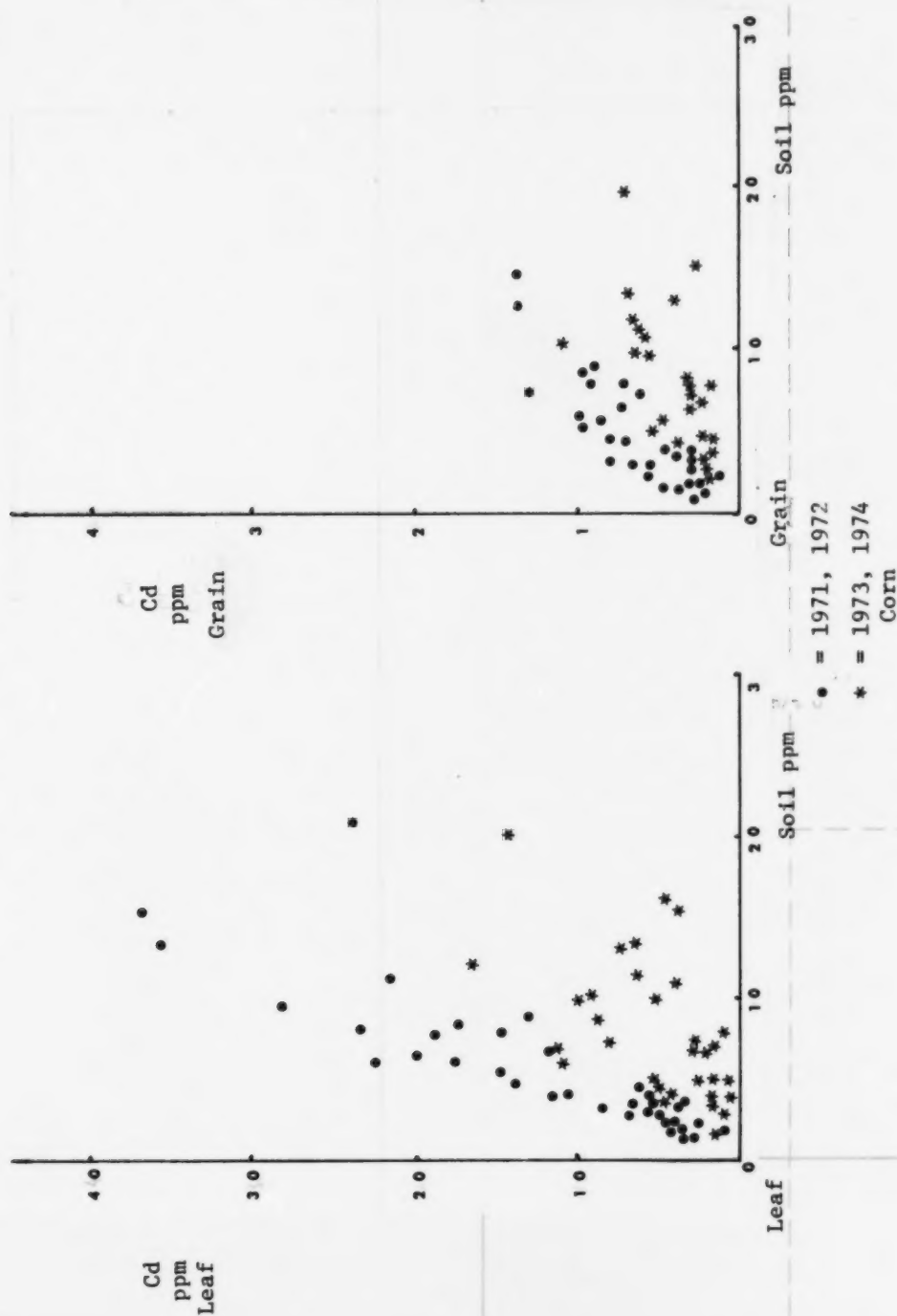


Figure 34. Leaf and grain levels by soil level.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

The relevance of these findings to the project objectives is twofold. First, these results show that the risk assessment must be based on longitudinal results from studies of particular design. In particular, we can now see what sort of study is required if the risk assessment is to be successful. Second, the actual conduct of the risk assessment is altered by the finding that the temporal sequence of applications may be important in determining the response of the crop system to the cadmium loading. It is the temporal distribution of patterns of sludge-borne cadmium applications to land that should be considered in the convolution with plant uptake characteristics. This is both a help and a hindrance, as the complexity of the process of risk assessment is materially increased by this feature of the system. On the other hand, this represents a possible control point from the point of view of risk control: i.e., feedback into the risk assessment. If the phenomenon may be used to create conditions unfavorable to efficient uptake, the risk assessment is altered to account for this possibility. Much more work needs to be done in this area.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

97

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

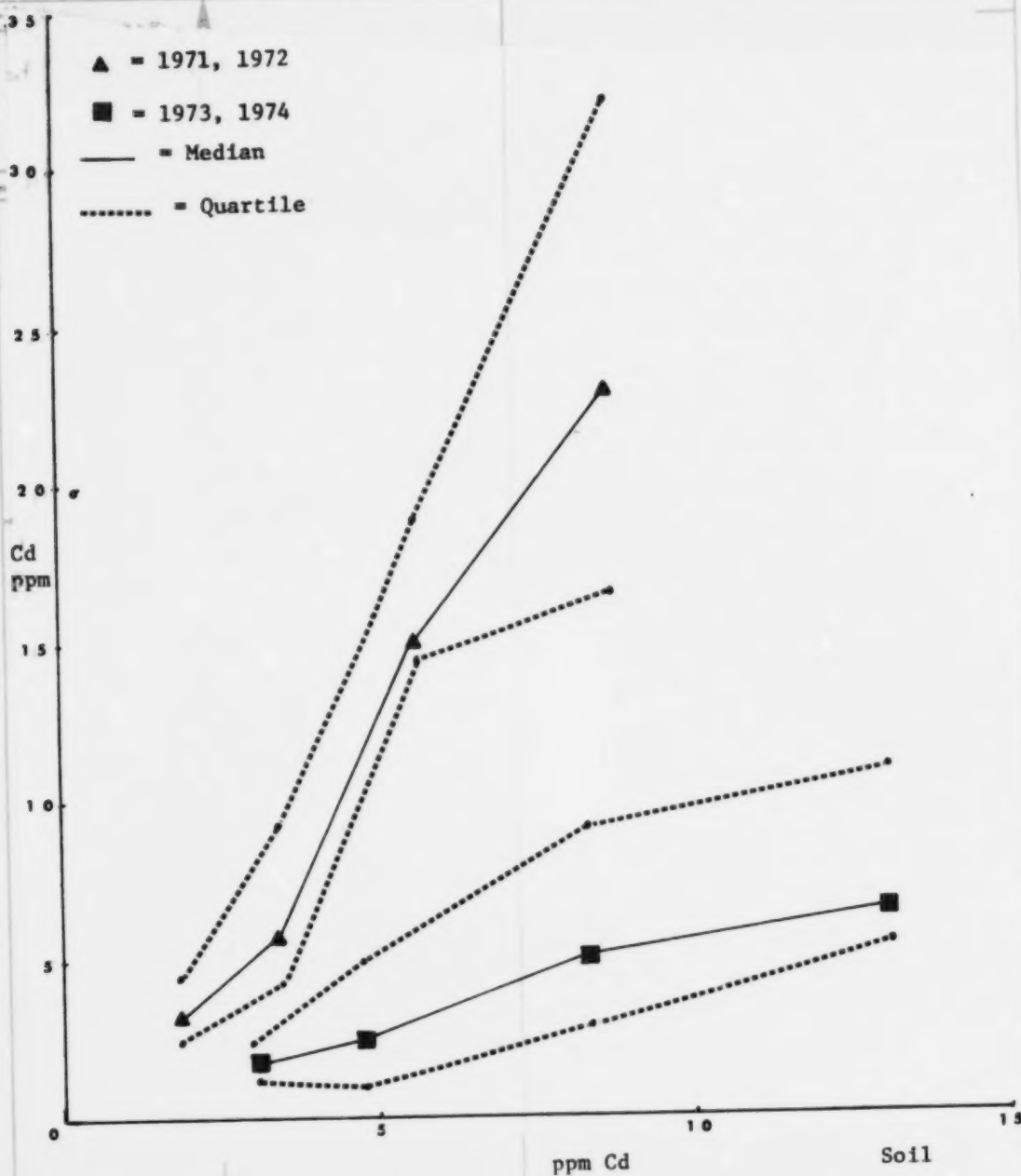


Figure 35. Leaf levels by soil cadmium.

BEGIN
LAST LINE
OF TEXT

3/8"

98

PAGE NUMBER

EPA-287 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

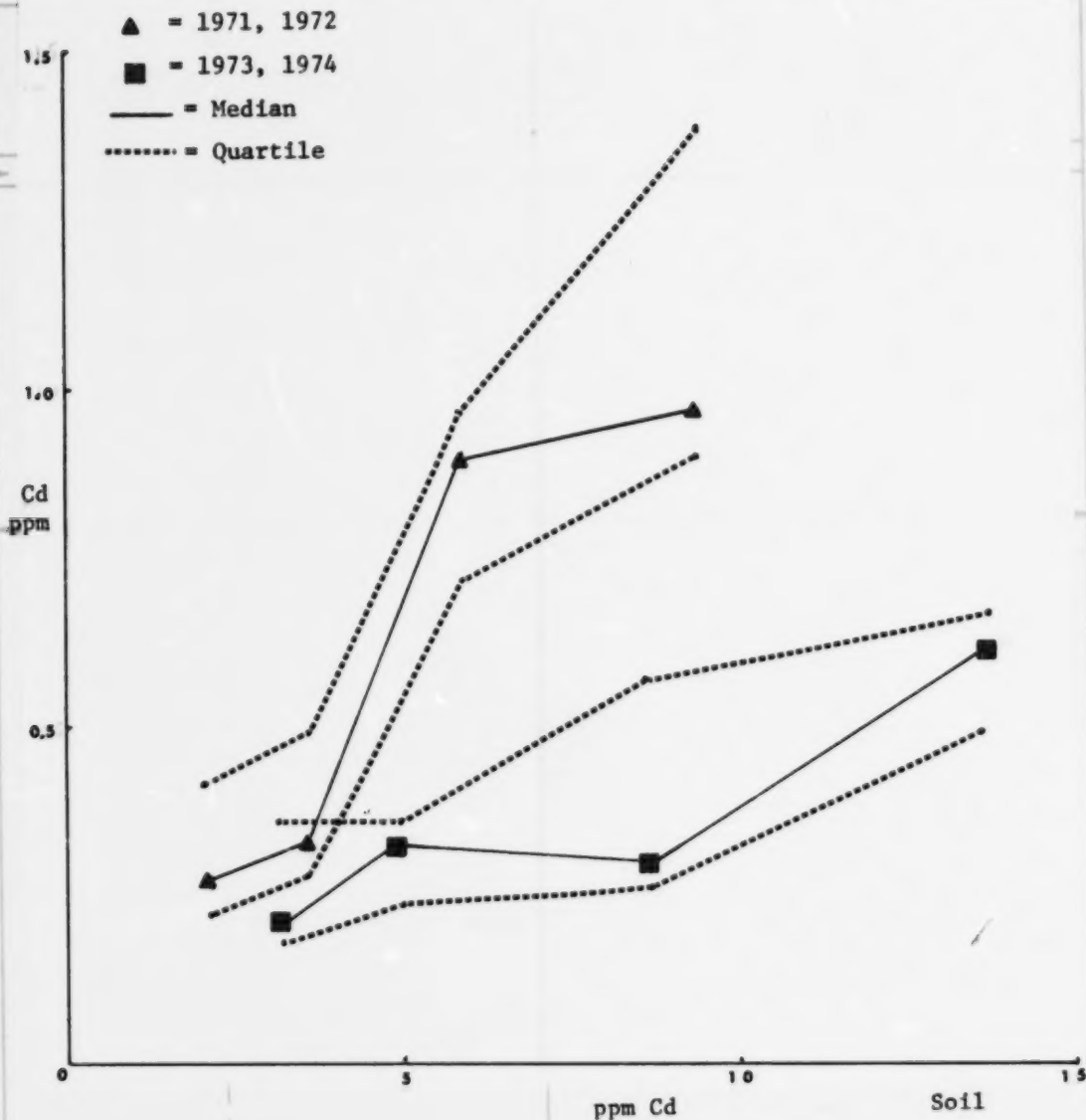


Figure 36. Grain levels by soil cadmium.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Summary of Plant Uptake Patterns

In the previous examples, culled from a larger selection we have studied, a clear pattern is presented. This pattern has policy relevance and affects on the feasibility of a risk assessment, which must be designed in a manner that reflects awareness of the properties of the physical system within which the risk arises. A summary of these properties, as they appear to be determined by the literature, follows.

1) Whatever its form, cadmium applied to the soil in which plants are grown is taken up by those plants, to varying degrees.

2) There are several substantial sources of variation in the amount (concentration) of cadmium taken up by the plant.

- a. plant species
- b. plant part (leaf, grain, stover)
- c. plant cultivar
- d. amount of recently applied cadmium in the soil
- e. total cumulative cadmium in the soil
- f. chemical form of the cadmium (salt, sludge-borne)
- g. pH of the soil
- h. soil type

Each of these may be considered a control point, and should be evaluated as such both in a risk assessment and in supporting research.

3) The pattern of land application should be considered, because the cadmium that is applied just before the growth year has a markedly greater rate of uptake than cadmium which applied some years before the growing season under study.

4) There is a tenfold or greater reduction in the amount taken up by the grain from the amount taken up by the leafy parts of the plant in the species considered. Leafy vegetables actually seem to be the most avid absorbers of cadmium.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

100

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

5) Plant vulnerability to other toxic substances is a check on the amount of cadmium applied in the form of sludge, although it may not be sufficient to protect from high levels of plant uptake.

6) The results of single-year studies, or those in which simulated sludge is used, may not be an accurate representation of the true pattern under actual field conditions. They should be interpreted with great caution.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

101

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 8

Animal Response to Crops Grown on Sludged Plots

(This section concerns Figure 14, stage VII, for animals)

The results of research into the effects on animals of ingestion of crops grown on sludged soils is relevant to the objectives of the study for two reasons. First, insofar as a risk assessment is contemplated for the ultimate exposure of humans, it must take into account the possibility of transmission (or blocking) of the threat in the animal intermediary in the food chain. Second, the risk assessment may use the results of observations of the health effects of animal exposure to estimate the risk posed to humans.

The second point, which would be very valuable to the process of risk assessment, is difficult to evaluate on the basis of the results so far obtained. There have been, to our knowledge, no demonstrated, quantifiable health effects in animals due to the long-term, continuous ingestion of feed with moderate cadmium levels such as those obtained in sludged plots. There is, therefore, no satisfactory input to the problem of assessing the risks of such a realistic regimen. There are results of high dose, acute toxicity responses, but those are of dubious value in assessing the risks from low dose, continuous exposure, such as is contemplated by the results of agricultural use of sludge. Low dose here means levels much less than acutely toxic, but larger than background. There are results which suggest that there is no measurable short-term damage resulting from non-acute exposures. In the work of Hinesly and Hansen (reference 10), in which various animal species have been fed crops from sludged land (which had considerable concentrations of cadmium), there has been no evidence of

BEGIN
LAST LINE
OF TEXT

3/8"

102

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

untoward effect in the short follow-up. One is, of course, understandably reluctant to give cadmium in food a clean bill of health just because there is no immediately apparent ill-effect. Presumably it is the long-term exposure that carries the risk at these levels, and to quantify these risks directly will require at least some longitudinal character in the experimental design.

The first issue, of transmission or blocking in the pathway to humans that passes through animals, is addressed in several studies. The results are very relevant to the risk assessment task, and are summarized below. See references 10 and 16.

1. Cadmium ingested by the animal is concentrated primarily in the liver and kidney.
2. Skeletal meat contains very little cadmium under any circumstances, and the levels are not perceptibly increased by ingestion of cadmium.
3. The uptake efficiency of the animal, with respect to cadmium, is inversely related to the concentration of cadmium in the diet, i.e., the more cadmium per gram in the food, the lower the fraction of that cadmium taken up and deposited by the animal. Although amounts in liver and kidney go up in response to increased exposure in the diet, the increase in uptake is lower at high levels than at low levels in the diet.

These facts have considerable impact on the risk assessment process. It seems that disposing of the liver and kidneys will prevent the cadmium taken up by the animal from being passed on to humans. This, therefore, appears to be an unambiguous control point deserving investigation. The final point has relevance to the human health risk aspect. If the generalization to humans is made, it would seem that there is a complex relationship between the exposure of the organism to the cadmium, and the deposition of the substance in the sites where the damage is done over the long

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
LAST LINE
OF TEXT

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

term. It is clear that there will be much to criticize about a policy that assesses risk to humans by means of exposure, unless that relationship is elucidated.

In sum, the place of animals in the pathway of cadmium can be viewed as a potential control point. The most critical contribution of the animal studies is not to this issue, which seems to be fairly clear, but to the harder question of response of the human system to exposure.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

2/8"

104

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

SECTION 9

Exploratory Association of Air Cadmium Level with
Mortality Attributed to Three Categorical Factors

(This section concerns Figure 19, stage XII)

Comparison of sludge management alternatives requires comparison of risks associated with land application and risks associated with pyrolysis for relative effects on population exposure and population response. Pyrolysis of sludge leads to air cadmium and incremental respiratory cadmium. Two types of studies are relevant. One is controlled experiments on ingestion of air cadmium, such as reference (7). Another is epidemiological study of association of air cadmium with health effects. The latter has the usual limitations; namely, it is a univariate analysis of what is a complicated multivariate problem. Thus an association must be reinvestigated later either by the aforementioned type of study or by immensely more elaborate multivariate methods. Notwithstanding, the authors considered it necessary to carry out a univariate analysis in order to see whether further research in this direction looks promising. It is the authors' conclusion that this is the case. (The next level of multivariate analysis would be a similar study relating to all heavy metals at once and to other features of large urban areas.) In 1971 an investigator (reference 17) found evidence supporting excess mortality from certain causes in high air cadmium level areas. The present authors have carried out exploratory data analysis in an attempt to verify and extend these results based on a longer term data base. The authors have obtained and analyzed mortality and air cadmium data at the county level. A description of the methodology follows.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Mortality Ratio

From computer tapes provided by the National Center for Health Statistics, covering mortality for the years 1968 through 1975, a file was created which contained, for each of three disorder categories, by county, the numbers of deaths for each category. The three categories of cause of death used were 1) nephritis and nephrosis, (NEPH) 2) hypertension, (HYPERT) and 3) hypertension with or without renal failure (HYPER).

Because of the geographic code non-uniformity, 1968 and 1969 were eliminated from consideration, leaving a six year base, 1970-1975, inclusive. County deaths, by disease category, were aggregated over the six-year period in order to stabilize the county mortality. These aggregated counts of deaths are referred to as "actual deaths".

In order to adjust for the varying age, race and sex compositions found across counties, an "expected deaths" estimate was calculated for each disease and each county by using the 1972 national death rates for each age-sex-race category and the 1972 demographic profile of the county. For each disease and each county:

$$\text{Expected deaths} = 6 \times (\sum_i n_i r_i),$$

where n_i = the county population in the i^{th} age-sex-race category, and r_i = the national death rate for the particular disease in that category. The factor of six converts the formula to a six-year estimate of deaths expected in that county. It should be noted that the selection of counties was made on the basis of availability of air quality measurements, and therefore the counties in the mortality file are a subset of the total U.S. counties. Since the standard rates are based on the entire national experience, the expected deaths computed above are not forced to sum to the total actual deaths, across counties, as they would be if all the counties had been included or if the rates had been based on the experience of the

BEGIN
LAST LINE
OF TEXT

3/8"

106

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

included counties. In all, mortality data was manipulated for 1100 counties.

To create a mortality ratio for each disease and county, the fraction "~~Actual Deaths~~ divided by Expected Deaths" was formed, thus:

Mortality ratio for county C = $(\sum_i \eta_{ci} E_i) / (\sum_i \eta_{ci} r_i)$, where η_{ci} = population of county C in the i^{th} age-race-sex category, r_{ci} = mortality rate in that category for the county C (observed), and r_i = mortality rate for the nation in that category. These considerations led to the choice of the 100 largest U.S. counties (in population) for analysis.

6-1/2"
Air Data

9-1/8"
Since there are often several stations reporting air levels of cadmium within a single county, and there are usually considerable variations over time in the output of each station. It was necessary to create a summary air level for each county that is as faithful as possible to the latent concept of "ambient level", so that we could use this quantity as a possible predictor of excess mortality.

A further consideration in the preparation of a summary is the necessity that there be at least some, and preferably a great deal of experience with the measurement of cadmium in the county. The authors have chosen to examine only those counties in which the history of continuous monitoring and frequency of measurement were sufficient to indicate that the values presented have some stability and accuracy. This requirement has restricted our investigation to the sixty-nine of the previously described 100 counties that had adequate measurement histories. The raw scatter plots are available in printout at Cornell.

BEGIN
LAST LINE
OF TEXT

3/8"

107

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

In an effort to clarify the trends in the data, the air levels have been broken into five groups, and the median air level for each group has been found. Against these medians, the medians of the corresponding groups of mortality ratios [MR], as well as the quartiles have been plotted in Figures 37, 38, 39. This gives a rough schematic of the "regression" of the mortality ratio on the air level.

This approach is preferable to the usual least squares regression approach for several reasons.

1) There is no reason to believe that the response is linear and considerable reason to suppose that it is not.

2) Both the dependent and the independent variables are measured with sizable error.

3) We have no good reason to suppose that the experimental error is distributed in a Gaussian fashion.

4) If one is in any sense dealing with a "sample", it is not of counties, for what we have is a "population" of counties, which is not in reference to a "parent". Presumably, if there is a reference population, it is the one consisting of repetitions, in time, of the conditions of ambient cadmium in each of the counties. In the language of the analysis of variance, we are dealing with the random effects model rather than the fixed effects model. See references 18 and 19.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

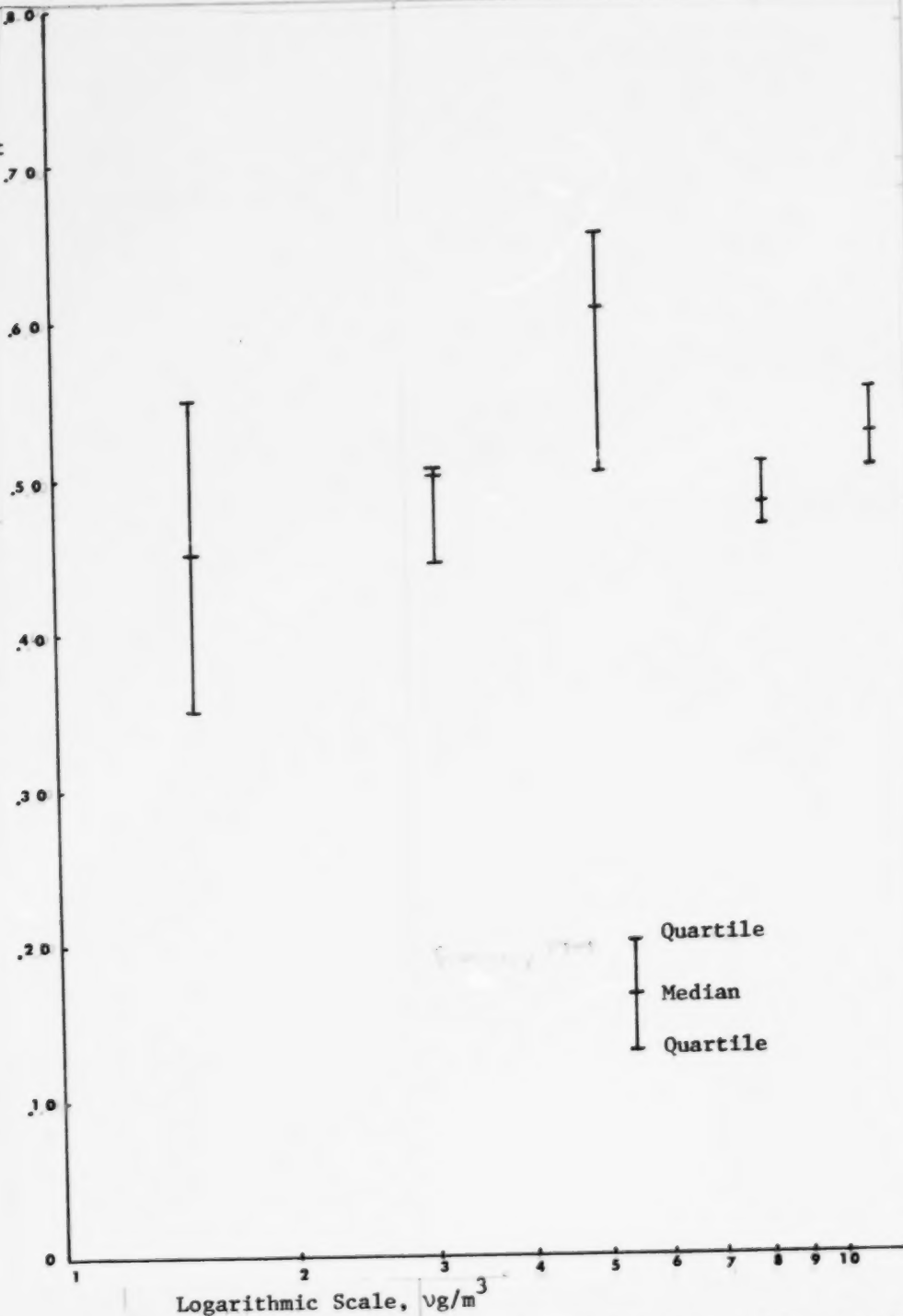
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

MR
Hypert



BEGIN
LAST LINE
OF TEXT

Figure 37. Summary plot: HYPERT - median air cadmium by mortality ratio.

3/8"

109

PAGE NUMBER

EPA-297 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

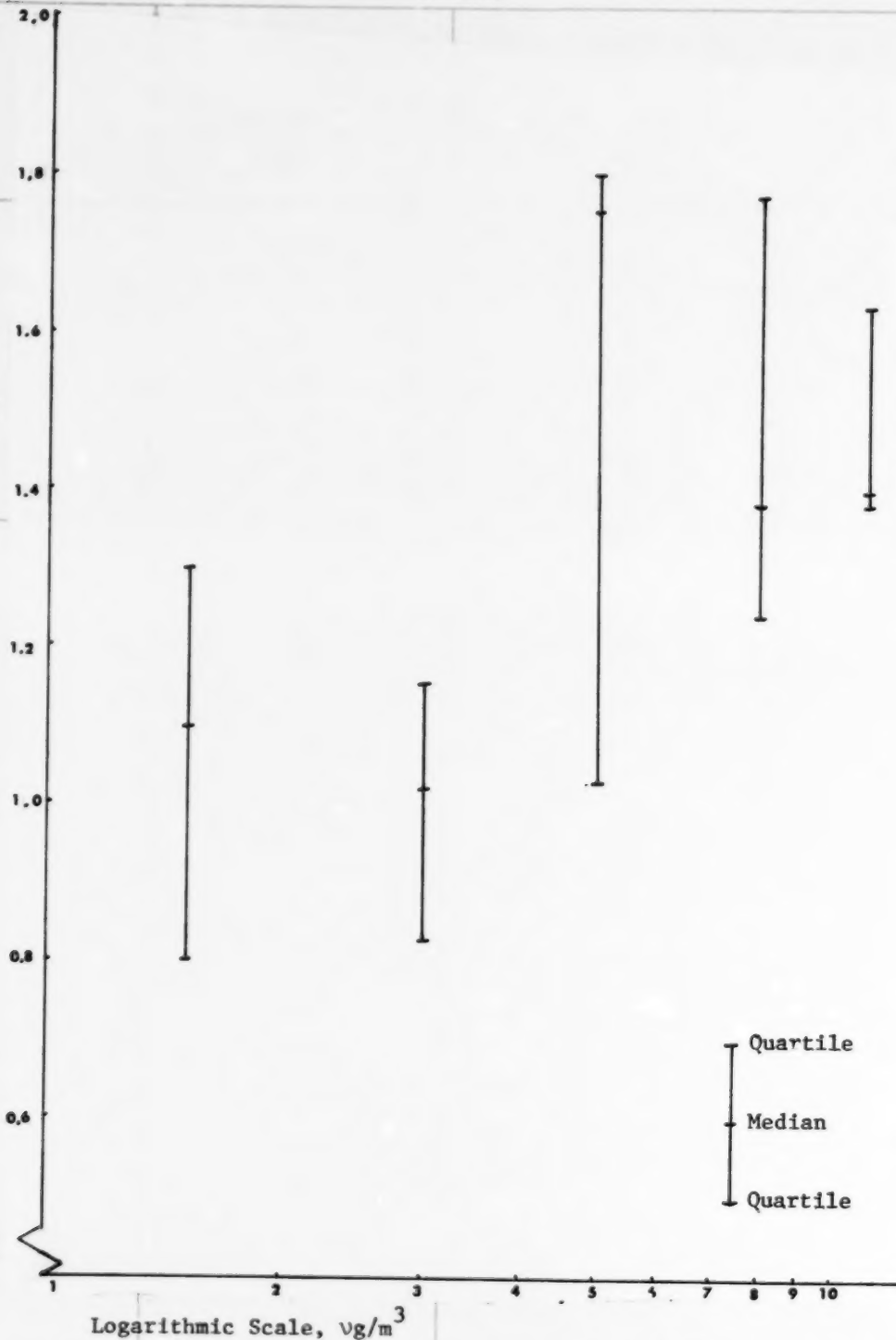
TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

MR
HYP



BEGIN
LAST LINE
OF TEXT

Figure 38. Summary plot: HYP - median air cadmium by mortality ratio.

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

MR
NEPH

1.2

1.1

1.0

0.9

0.8

0.7

0.6

Quartile

Median

Quartile

Logarithmic Scale, vg/m^3

BEGIN
LAST LINE
OF TEXT

Figure 39. Summary Plot: NEPH - median air cadmium by mortality ratio.

3/8"

111

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Examination of Figures 38 and 39 reveals strong evidence of a trend in both MRHYP and MRNEPH plots. In Figure 37 the MRHYPERT plot is ambiguous. There is a real possibility that the association of MRHYP and MRNEPH with air cadmium level is spurious, and due to confounding the cadmium level with some other variables which are the true carriers of the regression of mortality ratio. This cannot be ruled out without a complete multivariate analysis. This was beyond the scope of the present investigation, but is highly recommended. The intent of the present investigators was merely to point out the feasibility of using such associations to begin the population exposure and response calculations for pyrolysis of sludge.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

112

PAGE NUMBER

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Comparative Reanalysis with EPA Data

In order to strengthen the analysis of the aforementioned mortality patterns, the authors used EPA summary information (Table 7.5 in reference 20) about air cadmium levels for 1969 as an "independent variable" and the previously described mortality ratios as a "dependent variable" in a series of plots; one for each of the three disease categories. Although there is considerable overlap in these samples, there are also some counties for which the EPA provides summary information on yearly averages of cadmium in the air, but for which the existing data base of air measurements was considered too sparse for summarization by the procedure described above. For the purposes of this exposition, the summary charts in the Figures 40, 41, and 42 are given. Raw scatter plots are available at Cornell.

The authors have avoided the use of correlational methods to examine the association, or lack thereof, in the scatters. Instead, the authors have chosen to break the air data values into five categories, and to assign each category to a point on the abscissa corresponding to the median (parts per billion of cadmium) in the category. The mortality ratios for the counties in the category are plotted along the ordinate at that median, and the ordinates corresponding to the category median and quartiles of mortality ratio are marked. The resulting plot has the features of a regression, with error bounds, but is of a resistant character, and does not rely on distributional assumptions for its interpretation. See references 18 and 19 for an introduction to resistant methods.

The air cadmium categories have been chosen to be of appropriate size, and to be spaced at useful intervals along the abscissa. Because of the skew of the distribution of the air levels, the gaps between the three upper category medians are larger than the others in order to increase the precision at the critical region of the scatter. These plots follow, in Figures 40, 41, and 42.

It may be seen that the plots for HYPERT and NEPH are flat, indicating no association, whereas the plot for HYP is distinctly tilted, with a

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

BEGIN
LAST LINE
OF TEXT

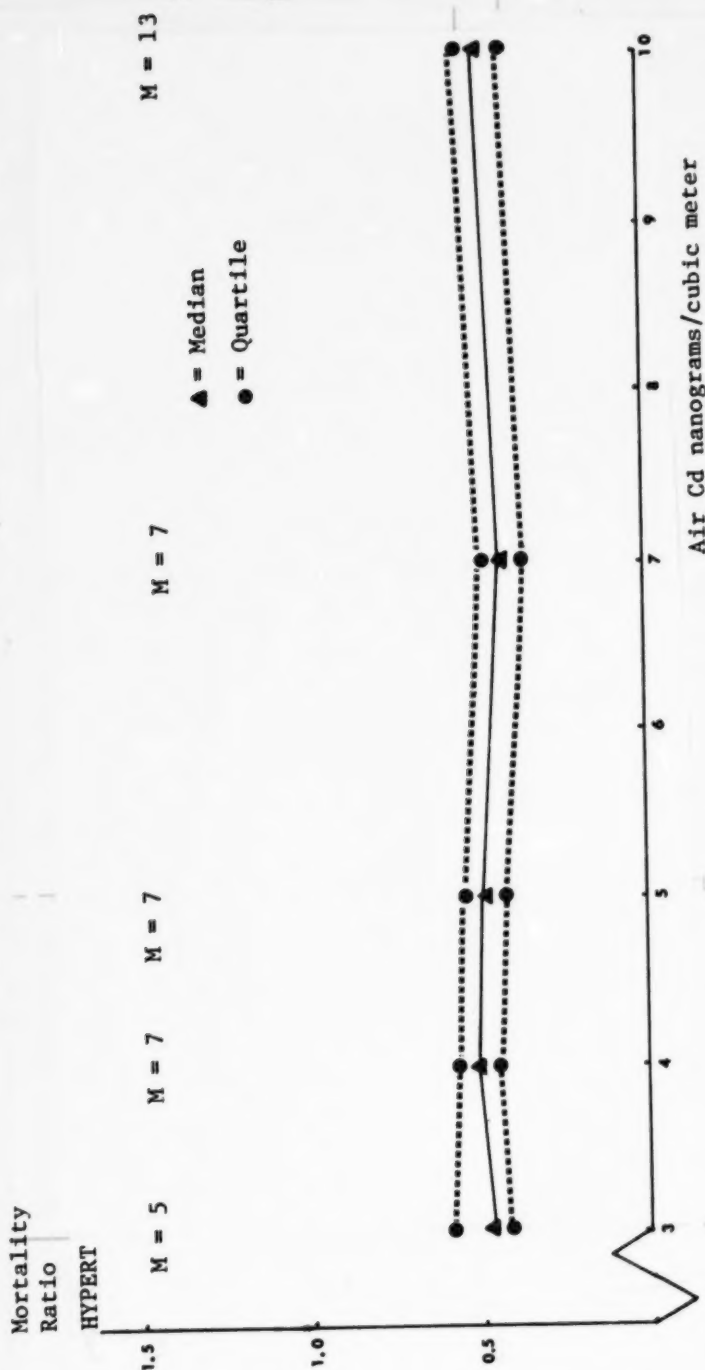
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE



The air levels have been divided into categories, and the median air level has been chosen for the abscissa. The median and upper and lower quartiles of HYPERT for each category are plotted on the ordinate. The M denotes the size of each category.

Figure 40. Mortality ratio for HYPERT, by EPA summary air levels of cadmium.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

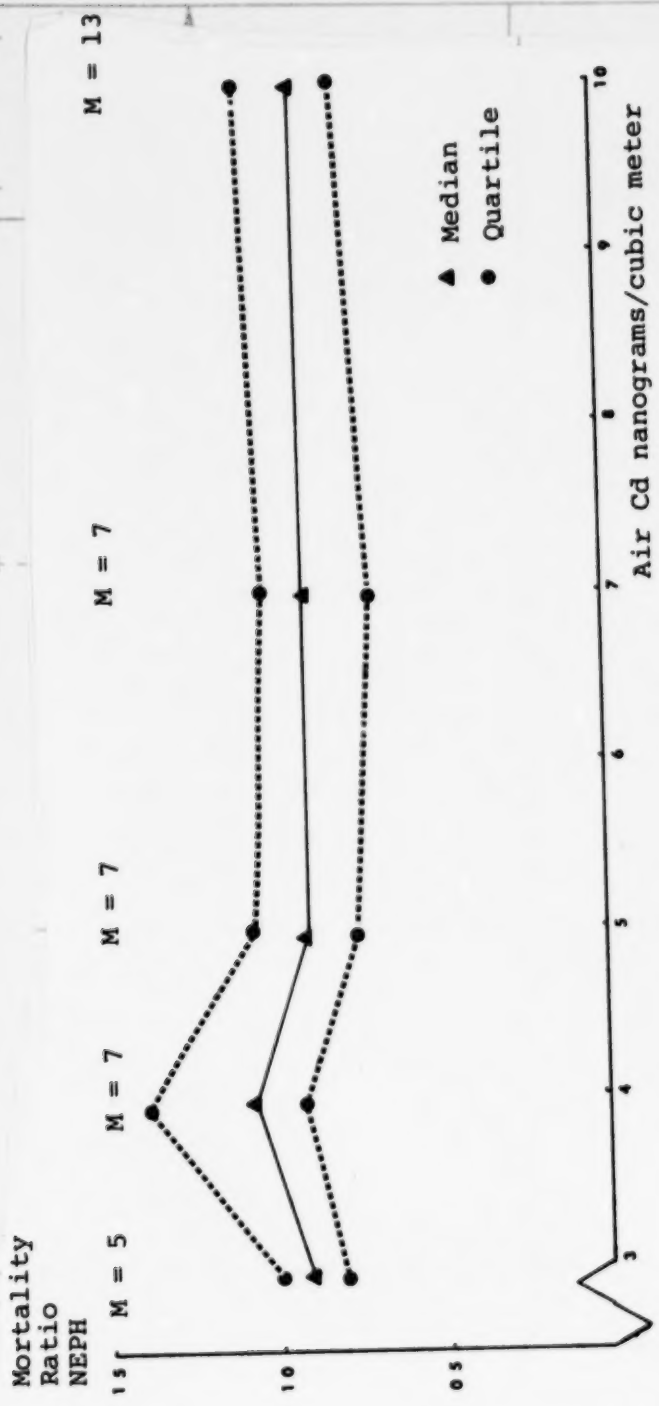
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE



The air levels have been divided into categories, and the median level has been chosen for the abscissa. The median and upper and lower quartiles of NEPH for each category are plotted on the ordinate. The M denotes the size of each category.

Figure 41. Mortality ratio for NEPH, by EPA summary air levels of cadmium.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

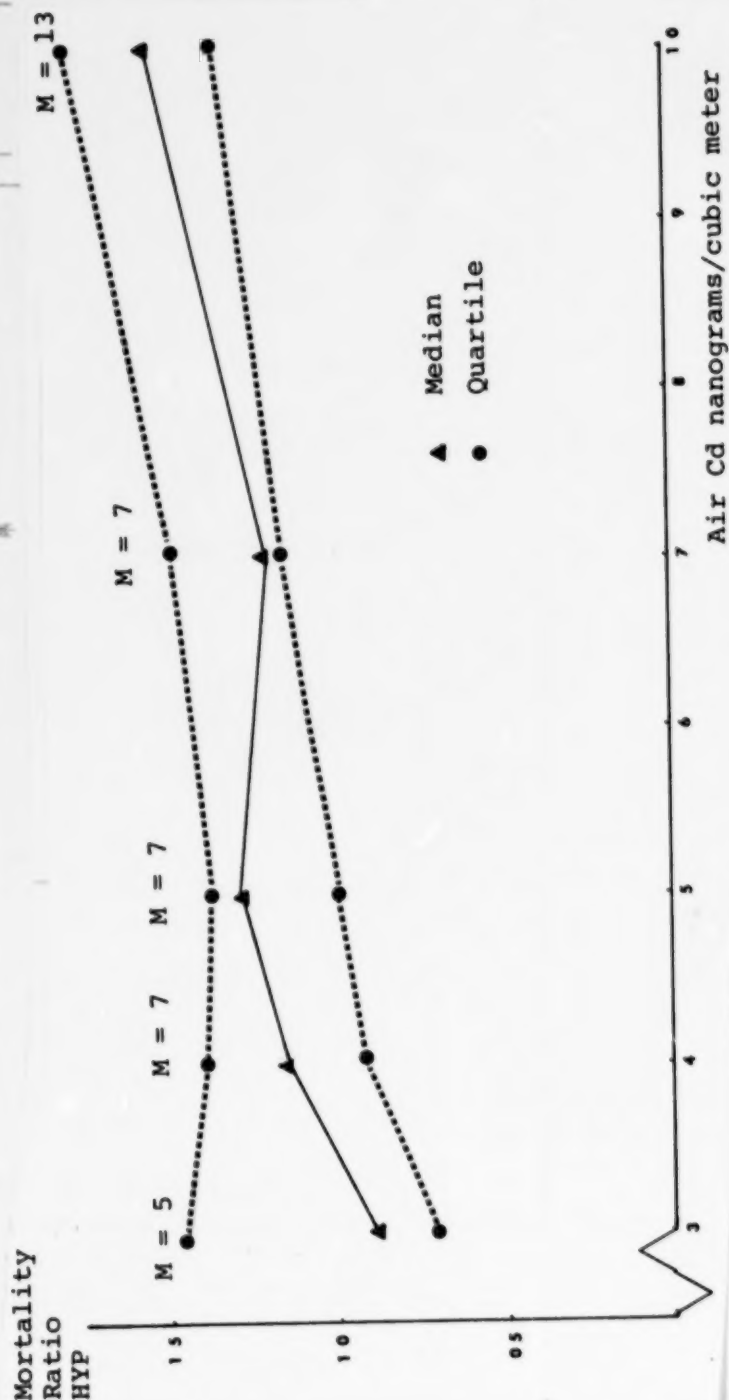
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE



The air levels have been divided into categories, and the median air level has been chosen for the abscissa. The median and upper and lower quartiles of HYP for each category are plotted on the ordinate. The M denotes the size of each category.

Figure 24. Mortality ratio for HYP, by EPA summary air levels of cadmium.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

clear and substantial trend. It appears that a threefold to fourfold increase in cadmium air levels is associated with about a 50% increase in mortality ratio in the region considered.

Discussion

The concluding remarks that follow discuss unresolved problems involved in upgrading air quality monitoring schemes so that the data can be used for population response analysis in a rational manner.

A typical county will have several air quality monitoring stations, each taking measurements on a more or less regular basis. As far as can be determined, generally, little thought has been given to the optimum pattern of sampling for measurement, and readings seem to be taken in a haphazard way. The potentials for bias are evident, and the problem must first be attacked by determining the objective of measurement. Presumably, from the public health point of view, one is interested in at least two distinct pieces of information that describe the cadmium (or other pollutant) exposure in the vicinity of the station. (The issue of station siting is left out of this discussion because it is treated in the following section.) These two parameters are

- 1) the average, in some suitably defined sense, exposure of a person in the area, as a function of time, and
- 2) the pulses of extreme exposure levels, and their distribution in time.

It is not the authors' intent here to propose candidates for these two parameters, but to point out that they are not adequately reflected in the current practice. The situation with regard to summarization in time at a particular station is compounded by the similar problem of summarization in space of the results of a group of stations operating within a particular political or demographic subdivision. Theoretically, one has in the data from the various stations in time, a sample from a cadmium density which is dependent on location and time. The summarization of these values as a temporal average of spatial averages is too naive to be of much use, and is

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

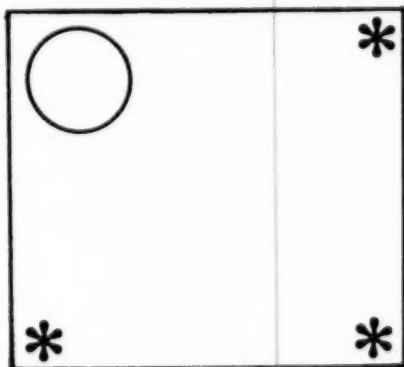
particularly sensitive to extreme values in either time or space. For these measurements to be of any value in risk assessment, they must be summarized in a way which is interpretable in the analysis.

The process of aggregating the sampling experience of a county, which may possess several stations, is a complex undertaking that influences the analytic process. It is easy to construct very plausible scenarios involving this process which result in severe biases in measurement. Fortunately, these biases are likely to occur in a consistent direction, and, therefore, may be partially mitigated, as we argue below.

To illustrate the problem, consider the following simple model of a county, which has one very intense source of cadmium discharge. This source has an appreciable effect on the ambient air level over the whole county at some distance from the source, but its local intensity is extremely high. One can now imagine at least three distinct measurement schemes involving the same number of sampling units, which differ only in the placement of the stations within the county, relative to the source.

Illustrations of these schemes follow. The large squares represent the county, the circle is the plume of the emitter, and each * is the location of a sampling station.

Scheme 1



BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

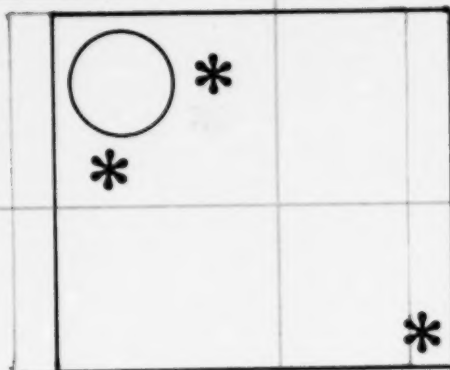
TYPING GUIDE SHEET

CENTER
OF PAGE

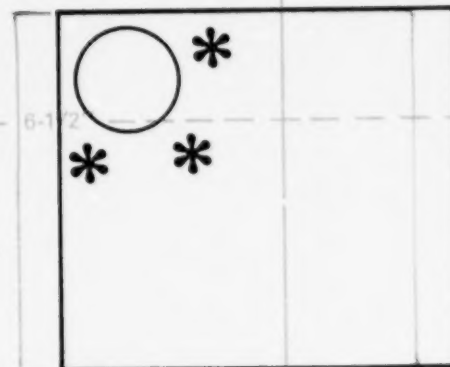
TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Scheme 2



Scheme 3



In scheme 1, the stations are all remote from the plume, perhaps reading from residential areas. In scheme 2, which is rather more common, there are two samples from the plume for each sample from the remote area. In scheme 3, all the measurements are taken from the plume. Under otherwise identical circumstances, (equal size of county, identical population distribution, same emitter) the schemes will generate radically different values of ambient air levels, unless the summary procedure is much more sophisticated than current methods. Scheme 1 in particular will yield low values, which, if the population is distributed mostly away from the emitter and its plume, will be a fairly accurate measure of the actual levels to which most of the population is exposed. Schemes 2 and 3 will produce measurements which are heavily influenced by the local emitter intensity, and which overestimate the population exposure. Scheme 3 will produce absurd levels, whereas scheme 2 may only introduce substantial bias.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

119

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

The effect of these biases on the regression analysis of a dependent variable (e.g., mortality) on the air levels is obvious. The absurdly high levels from scheme 3 will be recognizable to the human eye in a scatter plot, but will most likely wreak havoc in a packaged statistical computer algorithm. The more numerous and less obvious biases produced by the (more common) scheme 2 will produce a negative bias in the measurement of the regression; by stretching the independent variable the biases will lower the apparent trend or slope, and may even render the true association undetectable. It may be argued that in cases of populations which live within the plume of an emitter, scheme 1 underestimates the exposure, therefore overestimating the trend. Although this may occur, it is surely not as common as schemes 2 and 3, nor will its bias have as much scope.

It is the authors' belief that reorganizing the air quality monitoring schemes on a rational sampling basis would be a rewarding activity for the appropriate government entity, inasmuch as it would facilitate the conduct of risk assessment. The negative aspect of the reorganization would be the loss of continuity of records. This would support reorganization only for new measurement stations or moving only those existing measurement stations whose records of past measurements are so spotty as to be of little or no use. This remains a deserving topic for further research.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

REFERENCES

1. 15 USC 2605 (a).
2. House Report 94-1341, 94th Congress, 2d Session, at 14 (1976).
3. Committee on Principles of Decision Making for Regulating Chemicals in the Environment. Decision Making for Regulating Chemicals in the Environment. National Academy of Sciences, Washington, D.C. (1975).
4. Committee for the Working Conference on Principles of Protocols for Evaluating Chemicals in the Environment. Principles for Evaluating Chemicals in the Environment. National Academy of Sciences, Washington, D.C. (1975).
5. Lowrance, W.W. Of Acceptable Risk: Sciences and the Determination of Safety. William Kaufmann, Inc., Los Altos, California (1976).
6. Rowe, W.D. ^{9-1/8"} An Anatomy of Risk. John Wiley and Sons, New York (1977).
7. Ellis, K.J. Cadmium: In Vivo Measurement in Smokers and Non-Smokers. Science, pp. 323-324, 20 July (1979).
8. Baker, D.E., M.C. Amacher, and W.T. Doty. In: Land as a Waste Management Alternative; Proceedings of 1976 Cornell Agricultural Waste Management Conference, R.C. Loehr, Ed., Ann Arbor Science, Ann Arbor, Michigan (1977). pp. 261 ff.
9. U.S. Environmental Protection Agency (1978). Impact of Annual Cadmium Application Rates on Current Municipal Sludge Landspreading Practices.
10. Hinesly, T.D. and L.G. Hansen. Agricultural Benefits and Environmental Changes Resulting from the Use of Digested Sludge on Field Crops: Including Animal Health Effects. University of Illinois, Urbana, Illinois (1978).
11. Jones, R.I., T.D. Hinesly, and E.L. Ziegler. Cadmium Content of Soybeans Grown in Sewage-Sludge Amended Soil. Journal of Environmental Quality, 2(3):351-353 (1973).
12. Bingham, F.T., A.L. Page, R.J. Mahler, and T.J. Gianje. Growth and Cadmium Accumulation of Plants Grown on a Soil Treated with a Cadmium-Enriched Sewage Sludge. Journal of Environmental Quality, 4(2):207-211 (1975).

BEGIN
LAST LINE
OF TEXT

3/8"

121

PAGE NUMBER

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

13. Hinesly, T.D., D.E. Alexander, E.L. Ziegler, and G.L. Barrett. Zinc and Cd Accumulation by Corn Inbreds Grown on Sludge Amended Soil. Agronomy Journal, 70:425-428, May-June (1978).
14. Pettersson, O. Differences in Cadmium Uptake Between Plant Species and Cultivars. Swedish Journal of Agricultural Research, 7:21-24 (1977).
15. Chaney, R.L., S.B. Hornick, and P.W. Simon. Heavy Metal Relationships During Land Utilization of Sewage in the Northeast. In: Land As A Waste Management Alternative, R.C. Loehr, Ed. Ann Arbor Science, Ann Arbor, Michigan (1977).
16. Hinesly, T.D., E.L. Ziegler, and J.J. Taylor. Selected Chemical Elements in Tissues of Pheasants Fed Corn Grain from Sewage Sludge-Amended Soil. Agro-Ecosystems, 3:11-36 (1976).
17. Sprey, P. Association of Heavy Metal Levels in Ambient Air to Human Mortality in SMSA. U.S. Environmental Protection Agency, Washington, D.C. (1971).
18. Tukey, J.W. Exploratory Data Analysis. Addison-Wesley Publishing Company, Reading, Massachusetts (1977).
19. Mosteller, F. and J.W. Tukey. Data Analysis and Regression. Addison-Wesley Publishing Company, Reading, Massachusetts (1977).
20. Hammons, A.S., et al. Reviews of the Environmental Effects of Pollutants: IV. Cadmium. Prepared by Oak Ridge National Laboratory, Oak Ridge, Tennessee. EPA-600/1-78-026, U.S. Environmental Protection Agency, Cincinnati, Ohio (1978).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

122

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

BIBLIOGRAPHY

Blom, Bruce E., Sorption of Cadmium By Soils. Research Rept. No. 320. Pre-parpared for the National Science Foundation by Cold Regions Research and Engineering Lab, Hanover, New Hampshire, June 1974.

Bradshaw, A.D., "Pollution and Evolution." In: Effects of Air Pollutants on Plants, I.A. Mansfield, Ed., Cambridge University Press, England, no date.

Burge, Wylie D. and Paul B. Marsh, "Infectious Disease Hazards of Land Spreading Sewage Wastes." Journal of Environmental Quality, 7(1):1-9, January-March 1978.

Cadmium 77 Edited Proceedings, First International Cadmium Conference, San Francisco; Metal Bulletin, January 1978.

Cadmium Research Digest. International Lead Zinc Research Organization. No. 1 - 1976, No. 2 - 1977, New York, New York.

Calabrese, Edward J., Pollutants and High-Risk Groups; The Biological Basis of Increased Human Susceptibility to Environmental and Occupational Pollutants. John Wiley and Sons, New York, 1978.

Camp Dresser and McKee, Inc., Total Solids Management Program. Milorganite Analysis of Possible Health Risks. Prepared for Metropolitan Sewerage District of County of Milwaukee, Wisconsin, April 1978.

Cannon, Helen L. and Howard C. Hopps, Eds., Environmental Geochemistry in Health and Disease. Memoir 123, The Geological Society of America, Inc., 1971.

Carrington, E.G., The Contribution of Sewage Sludges to the Dissemination of Pathogenic Micro-Organisms in the Environment. Department of the Environment (U.K.), Wate Research Center, July 1977.

Citizens for A Better Environment, Milorganite Gardening - A Health Hazard. CBE-7802, March 1978.

Coleman, R., J. Lent, E. Burns, and P. Siebert, Atmospheric Cadmium: Population Exposure Analysis (Draft). Prepared by Energy and Environmental Analysis, Inc., for U.S. Environmental Protection Agency, Office of Air and Waste Management, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, March 17, 1968.

BEGIN
LAST LINE
OF TEXT

3/8"

123

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

Committee on Principles of Decision Making for Regulating Chemicals in the Environment, Decision Making for Regulating Chemicals in the Environment. National Academy of Sciences, Washington, D.C., 1975.

Comptroller General, Sewage Sludge - How Do We Cope With It? CED-78-152, U.S. General Accounting Office, September 25, 1978.

Conney, Jan, et. al., Report of the Workshop on the Health and Legal Implications of Sewage Sludge. Prepared by Energy Resources Company, Inc., for the National Science Foundation, February 1979.

Cooperative Extension Services of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, North Dakota, Ohio, Utilizing Municipal Sewage Wastewater and Sludges on Land for Agricultural Production. North Central Regional Extension Publication No. 52, November 1977.

Council for Agricultural Science and Technology, Application of Sewage Sludge to Cropland: Appraisal of Potential Hazards of the Heavy Metals to Plants and Animals. Report No. 64, EPA-430/9-76-013, U.S. Environmental Protection Agency Office of Water Program Operations, Municipal Construction Division, Washington, D.C., November 15, 1976.

Dames and Moore, Inc., Environmental Impact Statement on the Ocean Dumping of Sewage Sludge in the New York Bight (Draft). Prepared for U.S. Environmental Protection Agency, Region II, New York, New York, 1976.

DeHaan, F.A.M., Interaction - Mechanisms in Soil as Related to Soil Pollution and Groundwater Quality. Technical Bulletin 95, Institute for Land and Water Management Research, Wageningen, the Netherlands, 1976.

Department of the Environment (UK), Inventory of UK Research on Land Disposal of Sewage Sludge. Water Engineering 1, Research and Development Division, Technical Note No. 5, June 1976.

Department of the Environment (UK), National Water Council, Report of the Working Party on the Disposal of Sewage Sludge to Land. London, England, July 1977.

Department of the Environment (UK), Research Seminar on Pathogens in Sewage Sludge. Water Engineering 1, Research and Development Division, Technical Note No. 7, July 1977.

Department of the Environment (UK), Sewage Sludge Disposal Data and Technical Notes. Water Engineering 1, Research and Development Division, Technical Note No. 6, June 1977.

Elliott, L.F. and J.R. Ellis, "Bacterial and Viral Pathogens Associated With Land Application of Organic Wastes." Journal of Environmental Quality, 6(3):245-251, 1977.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Energy and Environmental Analysis, Inc., Evaluation of Municipal Wastewater Treatment Plant Operations Under the NPDES Permit/Enforcement Program. Prepared for U.S. Environmental Protection Agency, Office of Planning and Evaluation, March 13, 1979.

Energy and Environmental Analysis, Inc., Sources of Atmospheric Cadmium (Draft). Prepared for U.S. Environmental Protection Agency, Office of Air and Waste Management, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, February 1978.

Fertilizer Institute, Cadmium Seminar Summary Statements: California, October 12-13, 1978. Washington, D.C.

Flinn, James E. and R.S. Reimers, Development of Prediction of Future Pollution Problems. U.S. Environmental Protection Agency, Office of Research and Development, March 1974.

Friberg, Lars, Magnus Piscator, and Gunnar Nordberg, Cadmium of the Environment. CRC Press, 1971.

Gilbert, R.G., R.C. Rice, H. Bouwer, C.P. Gerba, C. Wallis, and J.L. Melnick, "Wastewater Renovation and Reuse: Virus Removal by Soil Filtration." Science, Vol. 192, June 4, 1976.

Gossett, James M., Utilization of Municipal Wastewater Sludge on Agricultural Lands... Public Health Aspects. Civil Engineering Department, Stanford University, March 20, 1974.

Guarino, Carmen F., Sergio S. Almeida, Michael D. Nelson, "Ocean Dispersal As An Ultimate Disposal Method." Presented at the 50th Annual Conference of the WPCF, October 3, 1977.

Hammons, Anna S., et. al. Review of the Environmental Effects of Pollutants: IV. Cadmium. ORNL-EIS-106, Oak Ridge National Laboratory, EPA-600/1-78-026, U.S. Environmental Protection Agency, Health Effects Research Laboratory, Office of Program Operations.

Hegg, Bob A., Kerwin L. Rakness, James R. Schultz, Evaluation of Operation and Maintenance Factors Limiting Municipal Wastewater Treatment Plant Performance. U.S. Environmental Protection Agency, Office of Research and Development, Municipal Environmental Research Laboratory, July 19, 1978.

Hemphill, D.D., Ed., Trace Substances in Environmental Health - III. Proceedings of the University of Missouri's 3rd Annual Conference on Trace Substances in Environmental Health. University of Missouri, 1970.

Hinesly, T.D., R.E. Thomas, and R.G. Stevens, Environmental Changes from Long-Term Land Application of Municipal Effluents. U.S. Environmental Protection Agency, Office of Water Program Operations. June 1978.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

Hoeks, J., Mobility of Pollutants in Soil and Groundwater Near Waste Disposal Sites. Technical Bulletin 105, Institute of Land and Water Management Research, Wageningen, the Netherlands, 1977.

Hoeks, J., Pollution of Soil and Groundwater from Land Disposal of Solid Wastes, Technical Bulletin 96, Institute for Land and Water Management Research, Wageningen, the Netherlands, 1976.

Hossner, L.R., et al., Sewage Disposal on Agricultural Soils: Chemical and Microbiological Implications, Vol I. EPA-600/2-78-131a, U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, June 1978.

Huber, Wayne C. and James P. Heaney, Urban Rainfall-Runoff-Quality Data Base. EPA-600/8-77-009, U.S. Environmental Protection Agency, Office of Research and Development, Municipal Environmental Research Laboratory, Cincinnati, Ohio, July 1977.

Interagency Regulatory Liaison Group (IRLG) Work Group on Risk Assessment, Scientific Bases for Identifying Potential Carcinogens and Estimating Their Risks. 1979.

Johnson, D.E., et al., Health Implications of Sewage Treatment Facilities. EPA-600/1-78-032, U.S. Environmental Protection Agency, Office of Research and Development, Health Effects Research Laboratory, Cincinnati, Ohio, May 1978.

Jones, Robert L, T.D. Hinesly, and R.J. Johnson, Agricultural Benefits and Environmental Change Resulting From the Use of Digested Sludge on Field Crops. Metropolitan Sanitary District of Greater Chicago, May 1973.

Kahn, Harold A., "The Dorn Study of Smoking and Mortality Among U.S. Veterans: Report on 8½ Years Observation," and Hammond, E. Cuyler, "Smoking in Relation to the Death Rates of One Million Men and Women." In: Haenzel, W., Ed., Epidemiological Approaches to the Study of Cancer and Other Chronic Diseases. National Cancer Institute Monograph No. 19. U.S. Department of Health, Education and Welfare, Public Health Service, 1966.

Keeney, Dennis R., Environmental Impact of Cadmium and Other Heavy Metals from Land-Applied Sewage Sludge. Water Resources Center, University of Wisconsin, Madison, Wisconsin, July 1976.

Kjellstrom, Tord, Accumulation and Renal Effects of Cadmium in Man. A Dose-Response Study. Department of Environmental Hygiene, Karolinska Institute, Stockholm, Sweden, 1977.

Latkin, Maurice H., James L. Smith, David B. McWhorten, On-Land Disposal of Municipal Sewage Sludge: A Guide to Project Development. Grant No.

BEGIN
LAST LINE
OF TEXT

3/8"

126

PAGE NUMBER

BOTTOM OF
IMAGE AREA:
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

AEN74-08082. Submitted to National Science Foundation, RANN, Regional Environmental System Division. Colorado State University, Fort Collins, Colorado, July 8, 1977.

Leeper, G.W., Reactions of Heavy Metals With Soils With Special Regard to Their Application in Sewage Wastes. Contract no. DACW 73-73-C-0026. Prepared for Department of the Army Corps of Engineers, November 1972.

Loehr, Raymond C., "Engineering Perspectives on the Application of Sludge to Land." Presented at Sludge Management and Ultimate Disposal Seminar Sponsored by James M. Montgomery Consulting Engineers, Inc., May 25, 1977, California.

Loehr, Raymond C., Ed., Land as a Waste Management Alternative. Proceedings of 1976 Cornell Agricultural Waste Management Conference. Ann Arbor Science, Ann Arbor, Michigan, 1977.

Lowrance, William W., Of Acceptable Risk: Science and the Determination of Safety. William Kaufmann, Inc., Los Altos, California, 1976.

Masironi, R., Ed., Trace Elements in Relation to Cardiovascular Disease. Cardiovascular Disease Unit, World Health Organization, Geneva, Switzerland, 1974.

National Academy of Engineering, Committee on Public Engineering Policy, Perspectives on Benefit-Risk Decision Making. National Academy of Engineering, Washington, D.C., 1972.

National Academy of Engineering - National Academy of Sciences, Coordinating Committee on Air Quality Studies, Air Quality and Automobile Emission Control Vol. II; Health Effects of Air Pollutants. Prepared for U.S. Senate, Committee on Public Works. Washington, D.C., September 1974.

National Academy of Sciences, National Research Council, Committee on a Multimedum Approach to Municipal Sludge Management, Multimedum Management of Municipal Sludge: Vol. IX. A report to the U.S. Environmental Protection Agency, Washington, D.C., 1978.

National Research Council, National Academy of Sciences, Commission on Natural Resources and the Steering Committee for Analytical Studies. Perspectives on Technical Information for Environmental Protection. Vols. I and II. A report to the U.S. Environmental Protection Agency, Washington, D.C., 1977.

National Research Council Safe Drinking Water Committee, Advisory Center on Toxicology, Assembly of Life Sciences, Drinking Water and Health. National Research Council, National Academy of Sciences, Washington, D.C., 1977.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

National Science Foundation, RANN, Division of Advanced Environmental Research and Technology, Ecosystems Processes and Organic Contaminants. Grant No. AEN-75-10632. NSF-RA-760008, 1976.

Okrent, David, Risk Assessment of Water Reuse. #78-20259, Research proposal to the National Science Foundation, Division of Advanced Environmental Research and Technology.

Page, A.L., Fate and Effects of Trace Elements in Sewage Sludge When Applied to Agricultural Lands. EPA-670/2-74-005, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, January 1974.

Page, A.L. and S.C. Chang, "Trace Elements and Plant Nutrient Constraints of Recycling Sewage Sludges on Agricultural Land." Presented before Second National Conference on Water Reuse: Water's Interface with Energy, Air, and Solids, Chicago, Illinois, May 4-8, 1975.

Pahren, Herbert R., James B. Lucas, James A. Ryan, and Kenneth G. Dotson, "An Appraisal of the Relative Health Risks Associated With Land Application of Municipal Sludge." Presented at the 50th Annual Conference of the Water Pollution Control Federation, Philadelphia, Pennsylvania, October 2-6, 1977.

Pier, Stanley M., "The Role of Heavy Metals in Human Health." Texas Reports on Biology and Medicine, 33(1), 1975.

Pound, Charles W., R.W. Critis, J. Olson, Metcalf, and Eddy, Long-Term Effects of Land Application of Domestic Wastewater: Hollister, California Rapid Filtration Site. U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, April 1978.

Regional Wastewater Solids Management Program, Los Angeles/Orange County Metropolitan Area Project, Risk Assessment of Heavy Metals and Trace Organics in Municipal Sludge Management. Technical Report No. 10, Whittier, California.

Rowe, William D., An Anatomy of Risk. John Wiley and Sons, New York, 1977.

Rudd, Robert L., Environmental Toxicology. Gale Research Co., Book Tower, Detroit, Michigan, 1977.

Sagik, Bernard P., and Charles A. Sorber, Eds., Risk Assessment and Health Effects of Land Application of Municipal Wastewater and Sludges. Center for Applied Research and Technology, University of Texas, San Antonio, Texas, 1978.

Scientific Committee on Problems of the Environment, International Council of Scientific Unions, Atmospheric Pathways of Sulphur Compounds. Monitoring and Assessment Research Center Report No. 7, 1978.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

128

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Smith, Albert E., et. al., Workbook for the Comparison of Air Quality Models (Draft). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Monitoring and Data Analysis Division, Research Triangle Park, North Carolina, November 1977.

Subcommittee on the Toxicology of Metals, International Association of Occupational Health, Toxicology of Metals - Vols. II and III. U.S. Environmental Protection Agency, Office of Research and Development, Health Effects Research Laboratory, Research Triangle Park, North Carolina, 1977-78.

Thorton, Sydney, The Use of Natural Vegetation to Determine The Degree of Environmental and Food Chain Pollution Caused by Airborne Lead and Cadmium. Air and Industrial Hygiene Laboratory, State of California, Department of Public Health, Berkeley, California, November 1971.

Tukey, John W., Exploratory Data Analysis. Addison-Wesley Publishing Company, Reading, Massachusetts, 1977.

U.S. Department of Agriculture, Agricultural Research Service, Factors Involved in Land Application of Agricultural and Municipal Wastes. July 1974, reprinted 1975.

U.S. Department of Health, Education and Welfare, Health Services & Mental Administration, Center for Disease Control, Ten-State Nutrition Survey 1968-70. DHEW Publication No. (HSM) 72-8133.

U.S. Department of Health Education and Welfare, Public Health Service, Center for Disease Control; National Institute for Occupational Safety and Health, Registry of Toxic Effects of Chemical Substances, Vols. I and II. 1977 edition.

U.S. Department of Health, Education and Welfare, Public Health Services, Office of the Assistant Secretary for Health, Office on Smoking and Health, Smoking and Health: A Report of the Surgeon General. 1979.

U.S. Department of the Interior, Office of Water Resources Research, Cadmium in Water: A Bibliography. WRSIC 73-209, Water Resources Scientific Information Center, Washington, D.C., March 1973.

U.S. Environmental Protection Agency Region II, Environmental Impact Statement on the Ocean Dumping of Sewage Sludge in the New York Bight. September 1978.

U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory. Environmental Pathways of Selected Chemicals in Freshwater Systems: Part II: Laboratory Studies. Inter-agency Energy - Environment Research and Development Program Report. EPA-600 7-78-074, Athens, Georgia.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

U.S. Environmental Protection Agency, Proceedings of the Hazardous Waste Research Symposium: Residual Management by Land Disposal. EPA-600/9-76-015, July 1976.

U.S. Environmental Protection Agency, Environmental Research Information Center, Technology Transfer, Office of Water Planning and Standards, Water Planning Division, Assessment of Rural Nonpoint Source Pollution -- A Model Based on the Universal Soil Loss Equation. EPA-440/3-77-018, November 1977.

U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Estimation of Risk from Carcinogens in Drinking Water. Research Triangle Park, North Carolina, May 1978.

U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Land Cultivation of Industrial Wastes and Municipal Solid Wastes Vol. I and II. EPA-600/2-78-140 a and b, August 1978.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Monitoring and Data Analysis Division, Interim Guidelines on Air Quality Models. Research Triangle Park, North Carolina, October 1977.

U.S. Environmental Protection Agency, Office of Air and Waste Management, Office Air Quality Planning and Standards, Aerometric and Emissions Reporting System Information. Research Triangle Park, North Carolina.

U.S. Environmental Protection Agency, Office of Research and Development, Carcinogen Assessment Group's Assessment of Carcinogenic Risk From Population Exposure to Cadmium in the Ambient Air (External Review Draft). May 1978.

U.S. Environmental Protection Agency, Office of Research and Development, Health Assessment Document for Cadmium (Draft). May 1978.

U.S. Environmental Protection Agency, Office of Research and Development, Health Effects Research Laboratory, Method Development and Monitoring of Polynuclear Aromatic Hydrocarbons In Selected U.S. Waters. EPA-600/1-77-052, Cincinnati, Ohio, November 1977.

U.S. Environmental Protection Agency, Office of Research and Development, Health Effects Research Laboratory, Respirable Particles and Mists in Mouse Pulmonary Infectivity Model. EPA-600/1-78-036, Research Triangle Park, North Carolina, May 1978.

U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, Long-Term Effects of Land Application of Domestic Wastewater. EPA 600/2-79-047, Ada, Oklahoma, February 1979.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

130

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

U.S. Environmental Protection Agency, Office of Solid Wastes, Special Wastes Branch, Guidelines for the Utilization and Disposal of Sewage Sludge (Draft). October 11, 1978.

U.S. Environmental Protection Agency, Office of Water Planning and Standards, Monitoring and Data Support Division, Summary of Information Relevant to the Development of A Comprehensive Strategy for the Control of Cadmium. August 1978.

U.S. Environmental Protection Agency, Office of Water Program Operations, Application of Sludges and Wastewaters on Agricultural Lands: A Planning and Educational Guide. Publication 235, Washington, D.C., March 1978.

U.S. Environmental Protection Agency, Office of Water Program Operations, Evaluation of Land Application System. EPA-430/9-75-001, Washington, D.C., March 1975.

U.S. Environmental Protection Agency, Office of Water Program Operations, Municipal Construction Division, Application of Sewage Sludge to Cropland: Appraisal of Potential Hazards of the Heavy Metals to Plants and Animals. MCD-33, EPA 430/9-76-013, November 1976.

U.S. Environmental Protection Agency, Office of Water Program Operations, Municipal Construction Division, Municipal Sludge Management: Environmental Factors. EPA 430/9-77-004, Washington, D.C., October 1977.

U.S. Environmental Protection Agency, Technology Transfer, Land Treatment of Municipal Wastewater Effluents Case Histories. January 1976.

U.S. Environmental Protection Agency, Technology Transfer, Land Treatment of Municipal Wastewater Effluents Design Factors - I and II. January 1976.

W.E. Davis and Associates, National Inventory of Sources and Emissions of Cadmium, Nickel, and Asbestos, Section I: Cadmium. Prepared for National Air Pollution Control Administration, Department of Health, Education, and Welfare, February 1978.

Weaver, R.W., et. al., Sewage Disposal on Agricultural Soils: Chemical and Microbiological Implications Volume II. EPA-600/2-78-131b, U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, June 1978.

Wolman, Abel, "Public Health Aspects of Land Utilization of Wastewater Effluents and Sludges." Journal of the Water Pollution Control Federation, pp. 2211-2218, November 1977.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

131

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

World Health Organization, Manual of the International Statistical Classification of Diseases, Injuries, and Causes of Death, Vol. 2
Alphabetical Index. Geneva, Switzerland, 1969.

Zenz, David R., James R. Peterson, David L. Brooman, and Cecil Lue-Hing,
"Environmental Impacts of Land Application of Sludge." Journal of the
Water Pollution Control Federation, October 1976.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

132

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

